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A Magnetometer Which Makes Use of the Magnetic Resonance of Protons

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A magnetometer is described which utilizes the nuclear absorption effect of protons. This meter is provided with automatic calibration circuits, which permit the measurement of the field intensity with an accuracy of ± 0.006%. Fields of application in which the apparatus could be used are indicated.

INTRODUCTION

IN several investigations a need arises for the measurement and stabilization of static magnetic fields and for the measurement of their homogeneity with a high degree of accuracy. Among the different apparatus offered for the solution of these problems, the simplest and the most accurate ones are those which utilize the nuclear magnetic resonance.

A magnetic field meter can be constructed based on the principles of the utilization of the nuclear induction effect [1] or of the nuclear absorption effect [2].

We will examine the advantages of the nuclear absorption effect in its use as a basis for the construction of a magnetic field meter. Let us place a few atoms of a para- or a diamagnetic substance in a uniform magnetic field H_0 directed along the z-axis. The magnitude of the field is such as to prevent any interaction between the nuclear spin magnetic moment and the magnetic moment of the outer electronic shells of the atom. At the same time let us act on these atoms by means of an alternating field. $H = 2H_m \cos \omega_r t$ which oscillates with the Larmor precession frequency and which is directed perpendicularly to the field H_0. Two cases can be considered here, according to the magnitude of the amplitude H_m.

1) H_m large, $H_m \gg \dfrac{1}{|\gamma|(T_1T_2)^{1/2}}$, where γ = nuclear gyromagnetic ratio, i. e., the ratio of the nuclear magnetic moment to the mechanical moment, T_1 = relaxation time, i. e., the time for attaining the thermal equilibrium, T_2 = period of precession of the nuclear moment in the interatomic field. A strong radiofrequency field will produce a rotation of the magnetization vector around the field H_0 synchronous with the field (precession). This vector will deviate from the z-axis in direct proportion to the proximity of H_0 to the resonance field H_r, according to the Larmor precession equation:

$$H_r = \frac{\omega_r}{2\pi\gamma'} \tag{1}$$

where γ' = gyromagnetic ratio in cgs units. For $H_0 = H_r$ the magnetization vector will make an angle of 90° with the z direction. If one measures the induction emf which appears in the coil which envelops the substance (the axis of the coil being directed along the y-axis), its maximum will correspond to the resonance condition ($H_0 = H_r$). By using the method of nuclear induction, we can make a magnetic field meter in which the measurement of H_0 is reduced to the measurement of ω_r. If an adequate frequency standard is available, ω_r may be measured to a high degree of accuracy.

2) H_m is small. The induction effect is then very small, but the conditions for the observation of the resonance absorption of the electromagnetic energy of the alternating field become optimum. The maximum of energy absorption lies in the region of resonance frequency as determined by Eq. (1). This effect is called the nuclear absorption effect and can also be utilized in the construction of a magnetic field meter in which the measurement of the field is reduced to a measurement of frequency.

It is not feasible to build a magnetic field meter which utilizes the induction resonance effect, because in order to detect a weakly oscillating field around the y-axis in presence of a strong field H_m along the x-axis it is necessary to introduce a series of regulating elements into the sample holder of the apparatus and then to shield the same carefully [3]. The sample holder of the magnetic field meter which utilizes the nuclear absorption effect can be made smaller and therefore can measure fields in greater detail.

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[1] F. Bloch, Phys. Rev. 70, 460 (1946)

[2] H. C. Torrey, E. M. Purcell and R. V. Pound, Phys. Rev. 69, 680 (1946)

[3] F. Bloch, W. W. Hansen and M. Packard, Phys. Rev. 70, 474 (1946)

GENERAL DESCRIPTION OF THE APPARATUS

We built an apparatus which utilizes the nuclear absorption effect of protons, their γ' ratio being accurately known. Fig. 1 is a block diagram of the apparatus.

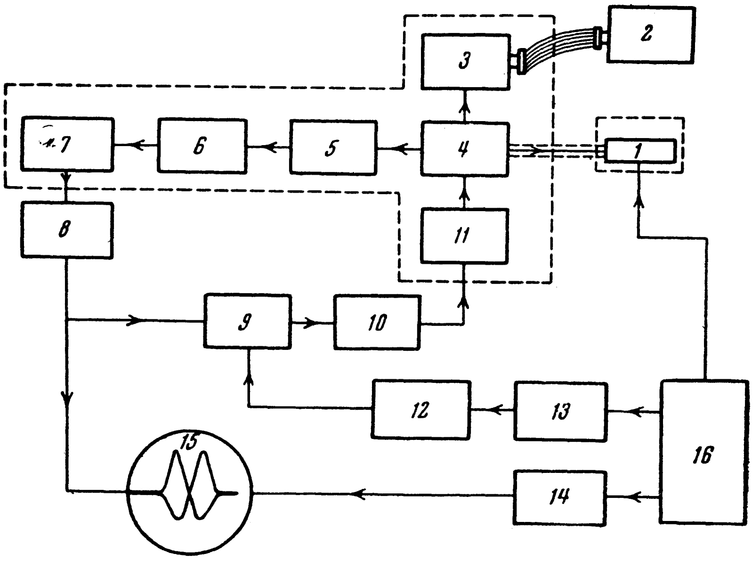

Fig. 1. Block diagram of the magnetic field meter: 1 - sample holder, 2 - heterodyne wavemeter, 3 - buffer stage, 4 - oscillator, 5 - detector, 6 - differentiating circuit, 7, 8 - signal amplifiers, 9 - phase detector, 10 - differential amplifier, 11 - reactance tube, 12 - square wave pulse generator, 13, 14 - phase changers, 15 - cathode-ray tube, 16 - 50 cycle source.

The sample holder is a thin-walled copper box which acts as an electrical and mechanical shield. A plastic toroidal vial is placed in this box of following dimensions; external diameter 15mm, internal diameter 3mm, height 6mm, wall thickness 0.2 mm. The vial is filled with a 10% solution of ferric chloride and a coil is wound around it to serve as the inductive coil of the oscillator. This coil is coupled to the oscillator by a coaxial cable of 500mm in length, which makes it possible to measure the field intensity at any point in the gap of a magnet of a diameter up to 1m and also to make quick changes of coils. The apparatus has 3 interchangeable sample holders with 3 coils wound around the vial in "PESHO 0.22" cable. The long wave, medium wave and short wave coils have 38, 22 and 6 turns respectively. The vial is surrounded by a plastic cover of 24mm diameter, on which the modulating coil is wound. This coil has 250 turns of "PE 0.2" cable. The modulating coil is fed by a. c. out of the 50 cycle mains. The modulation amplitude can be smoothly varied by varying the current in the coil from 0 to 120mA. The current is controlled by means of a device on the front panel of the meter. For measurements the sample holder is placed in the gap region of the magnet in such a manner as to make the axis of the modulating coil coincide with the axis of the measured field. To each value of the field, a value of the oscillator frequency ω_r can be found such that a pulse signal will appear on the oscillograph screen which corresponds to a quantum jump of the proton to a neighboring Zeeman level. Equation (1) is valid here. The oscilloscope beam is displayed along the horizontal axis by applying a voltage in phase and synchronous with modulating potential.

If the apparatus is made so that the impulses appear at times

$$t_0,\ t_0 + \frac{T_{\text{mod}}}{2},\ t_0 + T_{\text{mod}},\ \dots,$$

the modulating field will contribute no distortions to the measurement and $H_0 = H_r$ (Fig. 2). This condition corresponds to a calibration of the apparatus such that the peaks of coinciding pulses lie exactly in the center of the screen (during one modulation period 2 pulses appear on the screen). In our apparatus the pulses are differentiated and the base-point is selected as being the intersection of the near fronts of the differentiated pulses. From Fig. 2 one can see that the position of the base point on the screen corresponds to the position of the peaks of non-differentiated simultaneous pulses.

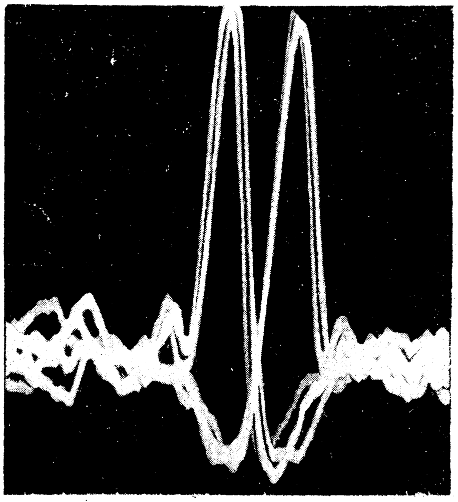

Fig. 2. A photograph of the pulse signal on the screen of the indicator tube.

The calibration of the apparatus reduces to a smooth variation of the oscillator frequency until the base-point is placed at the center of the screen, or, more exactly, in the middle of the sweep line, with a symmetrical modulating potential. Before the appearance of a pulse on the screen the calibration is performed by means of a vernier which modifies the capacity of the oscillator tuned circuit, while the sweep control (exact positioning of the base-point at the center of the screen) is obtained by means of automatic calibration circuits. By measuring the frequency of the oscillator (by means of the heterodyne wavemeter) it is easy to calculate the field intensity:

$$H_0 = 234.864\, f_r$$

where H_0 = field intensity in gauss, f_r = frequency in Mc/sec.

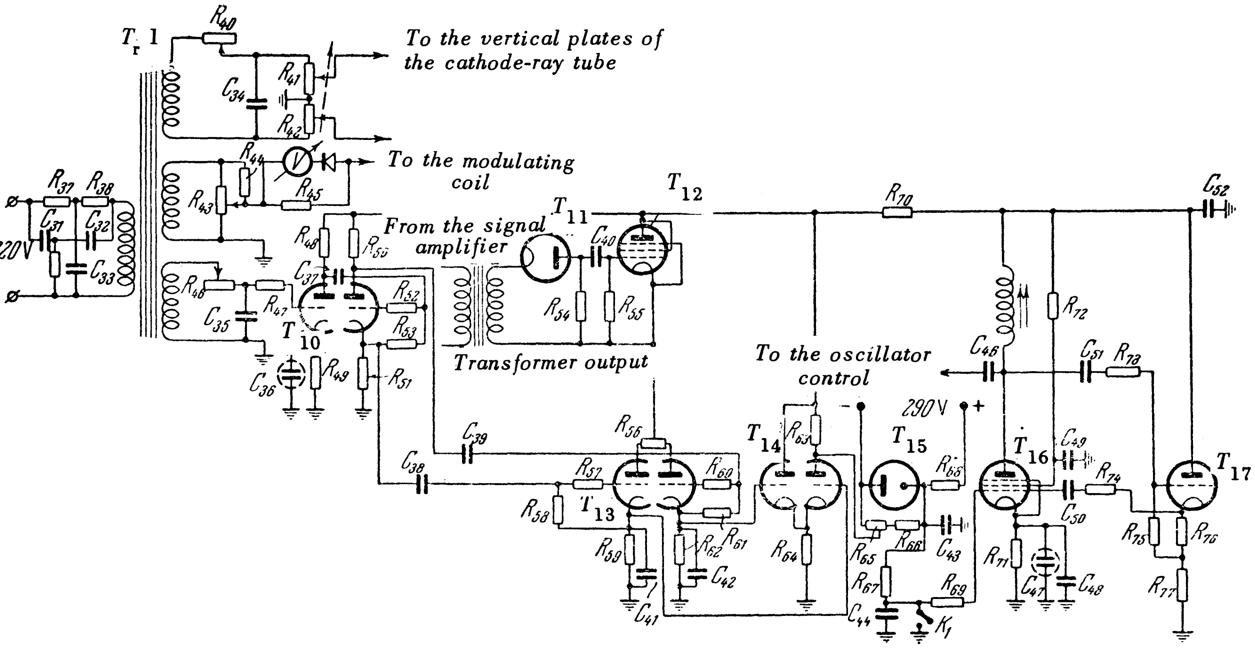

Fig. 3. Principal scheme of the automatic sweep control circuit. R_{37}, R_{38}, R_{73} - 1k Ω; R_{39} - 500 Ω; R_{40}, R_{46} - 5k Ω; R_{41}, R_{42} - 820 k Ω; R_{43} - 10 k Ω; R_{44}; R_{45} - 10 Ω; R_{46} - 5 k Ω; R_{47}, R_{52}, R_{54}, R_{55}, R_{56}, R_{57}, R_{58}, R_{60}, R_{61}, R_{77} - 510 k Ω; R_{48}, R_{50}, R_{51}, R_{66} - 100 k Ω; R_{49}, R_{71} - 2 k Ω; R_{53}, R_{63} - 1 M Ω; R_{59}, R_{62} - 51 k Ω; R_{64} - 30 k Ω; R_{65} - 160 k Ω; R_{67} - 10 M Ω; R_{68} - 12.5 k Ω; R_{69}, R_{72} - 50 k Ω; R_{70} - 24 k Ω; R_{74} - 400 k Ω; R_{75} - 70 k Ω; R_{76} - 200 k Ω; C_{31}, C_{32} - 1 μF; C_{33}, C_{44} - 2 μF; C_{34}, C_{35}, C_{43} - 0.25 μF; C_{36}, C_{47} - 100 μF; C_{37}, C_{38}, C_{39} - 0.5 μF; C_{40} - 0.02 μF; C_{41}, C_{42} - 12 μF; C_{46} - 20 μμF; C_{48}, C_{50}, C_{52} - 1000 μμF; C_{49} - 0.01 μF; C_{51} - 60 μμF; T_{10}, T_{13}, T_{14} - 6N9M; T_{11} - 6(KH)6; T_{12}, T_{16} - 6(ZH)3P; T_{15} - SG4S; T_{17} - 6(ZH)5

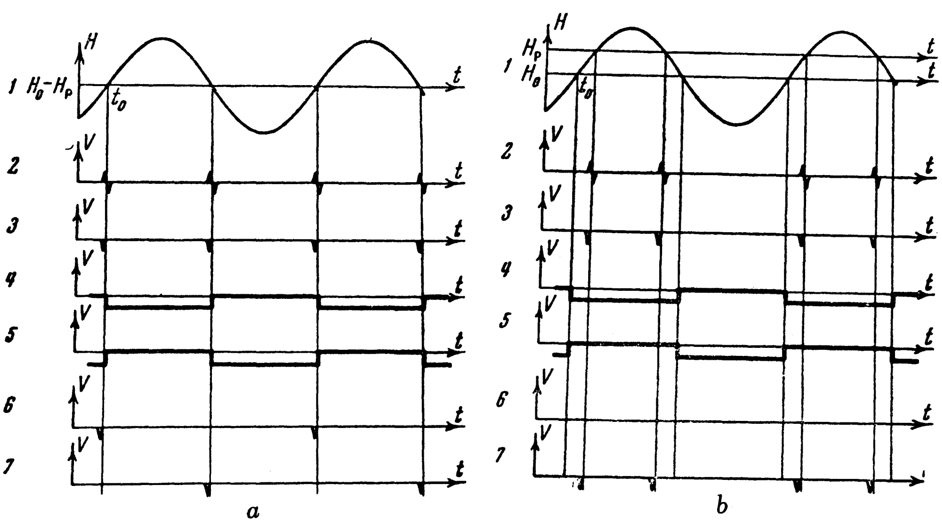

Fig. 4. Potential diagrams: *a)* $H_0 = H_r$, *b)* $H_0 \neq H_r$

1) Total intensity of the measured and the modulating fields

2) Signal on the cathode-ray tube

3) Potential on the grid of the tube T_{12}

4) Potential on the grid of the right-hand half of the tube T_{13}

5) Potential on the grid of the left-hand half of the tube T_{13}

6) Potential on the resistor R_{62}

7) Potential on the resistor R_{59}

AUTOMATIC CALIBRATION CIRCUIT

The basic part of the automatic sweep control circuit is the phase detector[4] (tubes T_{12} and T_{13}, Fig. 3.).

Square pulses in opposite phases are fed to the right and left-hand side circuits of the tube T_{13}. The pulses are formed by the square wave generator by using a potential in phase with, and synchronous to, the modulating voltage. The width of the square pulse is equal to the duration of a half-period of the modulating potential.

The amplitude of the square phase is such that at each moment one half of the tube T_{13} is non-conducting and the other is conducting. The pulse which is fed to the grid of T_{12} comes from the resistor R_{59} or from R_{62}, depending on which half of T_{13} is conducting. Figure (4a) gives the potential diagrams for the case when frequency of the generator corresponds to $H_0 = H_r$. One can see from Fig. (4) that the same number of pulses appears on the resistors R_{59} and R_{62}. Figure (4*b*) gives the potential diagrams for the case when the apparatus is not exactly tuned and the measured field is not equal to the resonance field. In this case no pulses will appear across R_{59}, all going to the resistor R_{62}. The potentials across R_{59} and R_{62} are integrated by the condensers C_{41} and C_{42}; the difference between these potentials, which changes in sign according to the direction of deviation of the oscillator frequency from the resonance frequency, is transmitted to the "deviation cascade" (reactance tube). The deviation cascade calibrates the generator frequency in order to keep it at the f_r value.

A general scheme of the automatic calibration circuits appears in Fig. (3). The voltage from the power transformer is applied to the horizontal deflection plates of the cathode-ray tube, the modulating coil and the square wave generator.

A double T filter is introduced into the primary circuit of the power transformer in order to obtain a better potential pattern in the secondary winding. The filter is tuned to the third harmonic of the circuit. The resistor R_{40} and the capacity C_{34} constitute a simple phase changer. It compensates for the phase shift between the modulating coil and the cathode-ray tube sweep circuits. The resistor R_{46} and the capacity C_{35} represent another phase changer which compensates the phase shift between the square wave generator and the modulating coil circuits. Two stages in the T_{10} tube circuit transform the sine signal into a square wave. The resistor R_{49} following the cathode of the first tube permits one to obtain a positive and

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[4] N. A. Shuster, Rev. Sci. Instr. 22, 254 (1951)

a negative pulse of the same width. The square pulses are transmitted respectively to the right-hand and the left-hand side triodes of the T_{13} tube of the phase detector. By means of the potentiometer R_{56}, on changing the T_{13} tube, one can always calibrate the phase detector so that with the signal absent the voltage across R_{59} is always equal to the voltage across R_{62}. The tube T_{11} cuts off the negative part of the differentiated signal pulse. On the anode of the differential amplifier T_{14} a voltage is obtained proportional to the difference of voltages obtained respectively across R_{59} and R_{62}. The magnitude of the constant anode voltage of the right-hand side of T_{14} is neutralized by the voltage drop across the resistor R_{66} and a part of the variable resistor R_{65} in parallel with the voltage stabilizer tube T_{15}. The voltage across the voltage stabilizer is provided by a separate rectifier. By means of the potentiometer R_{65} (on changing T_{15}) a zero potential is established between the grid of T_{16} and the ground. With a correct tuning of the automatic calibration circuit the voltage between the grid of the T_{16} tube and the ground will be zero (for in this case the base point lies exactly at the center of the screen), or will be negative (the base point is deflected to the right of the center), or positive (b. p. deflected to the left). On deflection of the base point to the border of the screen this voltage is ± 25 V. The parameters of the "deviation cascade"[5] (tubes T_{16} and T_{17}) are such that on changing the voltage on the grid of the tube T_{16} from −2 to −6 V, with a constant modulating voltage, the frequency of the oscillator changes so as to make the base-point traverse the whole screen from one extremity to the other. With a deviation on the T_{16} tube equal to −3.75 V, which is obtained by the deviating resistor R_{71} ($2k\,\Omega$), the operating point of the deviation cascade will lie in the middle of the linear part of the characteristic deviation curve. A negative voltage with respect to the ground, applied to the grid of T_{16} will make the base point deviate to the left; a positive voltage, to the right. With such calibration of the automatic circuit the base point will be automatically positioned at the center of the screen, provided a previous manual calibration brings the pulses at least up to the border of the screen. The time constant of the automatic calibration circuits is such that the base point moves from one border of the screen to the other in a time interval of one minute. To shorten the observation time and to obtain a greater accuracy it is necessary to bring the base point as near as possible to the center of the screen by manual tuning. A tumbler switch K, grounds the circuit of the T_{16} tube and thus disconnects the whole automatic calibration circuit.

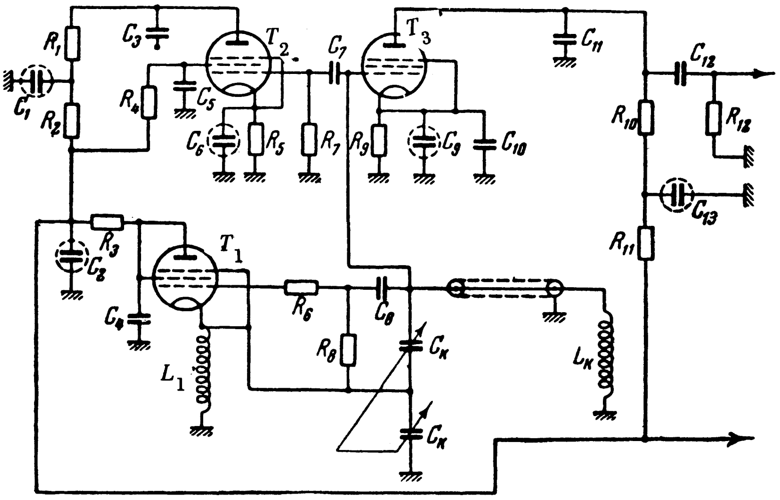

Fig. 5. Main circuit diagram of the oscillator, detector and the buffer stage. R_1 - 500 Ω; R_2 - 1 kΩ; R_3, R_9, R_{11} - 24 kΩ; R_4 - 50 kΩ; R_5 - 500 Ω; R_6 - 325 Ω; R_7 - 1 MΩ; R_8 - 70 kΩ; R_{10}, R_{12} - 100 kΩ; C_1, C_2 - 10 μF; C_3 - 20 μμF; C_4, C_5, C_{11} - 0.01 μF; C_6, C_9 - 100 μF; C_7 - 100 μμF; C_8, C_{12} - 60 μμF; C_{10} - 0.005 μF; C_{13} - 10 μF; C_k - 17 ÷ 550 μμF; T_1, T_2, T_3 - 6(ZH)3P; L_1 - 10 μH

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[5] H. D. Holerich, Electronics 4, 120 (1948)

OSCILLATOR AND THE OTHER STAGES OF THE METER

The oscillator consists of a (ZH) 3 tube, connected as a triode, in a capacitively coupled circuit (tube T_1, Fig. 5). This circuit allows the coupling of the control coil, which lies in the gas of the magnet which is being measured, with a coaxial cable with a grounded external lead. The resistance of the feedback coupling, R_6 regulates the amplitude characteristic of the oscillator according to the frequency sweep range. A block of 3 variable condensers and 3 variable coils on the oscillator covers a range of frequencies from 4.25 to 30 Mc/sec, corresponding to fields from 1000 to 7000 oersteds. The oscillator allows the broadening of the measurement range in both directions, if additional exchange coils are provided. A preliminary reading of the frequency is made on the vernier and the final reading is made on the heterodyne wave meter.

The tube T_3 constitutes the anode detector. The use of the T_1 tube as an oscillator (grid, cathode, screen grid) and as a detector (cathode, grid, anode), simultaneously, gives worse results, because it is difficult to find a value for the deviation voltage which is at the same time optimum throughout a large frequency range both for the oscillator and the detector.

The buffer stage (tube T_2) permits one to eliminate any influence of the heterodyne wavemeter on the oscillator, because of the weak coupling and of the small amplification factor.

The resistor R_{12} and the capacity C_{12} constitute a differentiating circuit, from which the signal goes to the signal amplifier, which has 5 stages. The output stage has a push-pull transformer coupling. The transformer is provided with 2 secondary windings. One applies the signal to the vertical deflecting plates of the cathode-ray tube, the other applies the signal to the input of the phase detector. The maximum amplification factor of the amplifier is about 10^6. The potentiometer in the circuit of the third stage permits a smooth regulation of the amplification factor. The transmission band of the amplifier is from 30-20,000 cps, with a sharp decrease of the amplification on the edges of the band.

The anode voltages of all the tubes are stabilized by an electronic stabilizer, which supplies a 265 V, 80 mA regulated voltage, with a noise of 2-3 mV. The filaments of T_1, T_2, T_3, T_{16} and T_{17} (figs. 3 and 5) are connected in series and are fed from a 0.3 B 17-3B rectifier with a selenium column. The total power utilized by the apparatus is 160 W. A cathode-ray tube of the 13L037 type was employed for visualization purposes. The supply circuit of this tube is analagous to that in the EO-4 oscillograph.

The actual construction of the apparatus employs two racks: the smaller one contains the oscillator, the detector, 2 signal amplifier stages, the buffer and the deviation stages; the other contains the remaining circuits. This construction permits use of the apparatus in the case where there is little space left near the magnet whose field is to be measured. The racks are interconnected by means of 2 cables. One transmits the signal and the other (a multiple cable) provides the supply and the reactance tube voltages.

APPLICATIONS OF THE APPARATUS

The above descrived meter has been used for exact measurements with permanent magnets. Measurements on one of them (of 24,000 oersteds), over many days, after a previous magnetic aging and maintained at a constant temperature, have shown that the maximum deviation from the mean value of 10 measurements constitutes + 0.006% The same degree of accuracy can be obtained by observing the sound tone in the phones of the heterodyne wavemeter by connecting it to the buffer stage. On connecting the automatic calibration circuit the frequency of the generator does not stay constant: it changes slowly about its mean value. The maximum frequency deviation which can thus be detected is 600 cps with a generator frequency of 10 Mc/sec this constitutes 0.006%. On measuring stronger fields the relative frequency oscillation is less. The absolute precision of the apparatus was not verified, because no other methods were available which would measure the magnetic field with the same accuracy as ours. Besides the measurements with permanent magnets, measurements have been effected on the aging of permanent magnets, the variations of the intensity of the field of an electromagnet fed by a storage battery of great capacity, and of the homogeneity of the field of a magnet. The apparatus can also be used for the measurement of instantaneous values of alternating fields.

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Translated by B. Cimbleris
10