

Lawrence Berkeley National Laboratory

Recent Work

Title

Magnetic Field Measurements by Nuclear Resonance

Permalink

<https://escholarship.org/uc/item/4xt7r93b>

Author

Kafitz, Peter

Publication Date

1948-08-20

DECLASSIFIED

UCRL 184 Cy 82/A

~~RESTRICTED~~

UNIVERSITY OF
CALIFORNIA

*Radiation
Laboratory*

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545*

BERKELEY, CALIFORNIA

UCRL-184
C.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

[illegible]

DECLASSIFIED

~~RESTRICTED~~

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

CLASSIFICATION CANCELLED
BY AUTHORITY OF THE DECLASSIFICATION
BRANCH USAEC *per TIO 1109*
BY *B. Robert* *1-31-56*
SIGNATURE OF THE DATE
PERSON MAKING THE
CHANGE

MAGNETIC FIELD MEASUREMENTS BY NUCLEAR RESONANCE

Peter Kafitz

August 20, 1948

Special Review of Declassified Reports

Authorized by USDOE JK Bratton

Unclassified TWX P182206Z May 79

REPORT PROPERLY DECLASSIFIED

<i>J N Green</i>	<i>8/16/79</i>
Authorized Derivative Classifier	Date
<i>R K Hunt</i>	<i>8/17/79</i>
By	Date

Berkeley, California

DECLASSIFIED

UCRL 184
Physics-Instrumentation

-2-

STANDARD DISTRIBUTION: Series A

Copy Numbers

RESTRICTED

Argonne National Laboratory	1-8
Armed Forces Special Weapons Project	9
Atomic Energy Commission, Washington	10-11
Battelle Memorial Institute	12
Brookhaven National Laboratory	13-18
Carbide & Carbon Chemicals Corporation (K-25 Area)	19-22
Carbide & Carbon Chemicals Corporation (Y-12 Area)	23-26
Columbia University (Dunning)	27
Columbia University (Failla)	28
General Electric Company	29-32
Hanford Directed Operations	33-39
Iowa State College	40
Kellex Corporation	41-42
Los Alamos	43-44
Massachusetts Institute of Technology	46
Monsanto Chemical Company, Dayton	47-48
National Bureau of Standards	49-50
Naval Radiological Defense Laboratory	51
NEPA	52
New York Directed Operations	53-54
Oak Ridge National Laboratory	55-62
Patent Advisor, Washington	63
Technical Information Division, ORDO	64-78
UCLA Medical Research Laboratory (Warren)	79
University of California, Radiation Laboratory	
Information Division	80-82
Chemistry, Bldg 5	83
Patent Department	84
University of Rochester	85-86
Western Reserve University (Friedell)	87
Chicago Office of Directed Operations	88

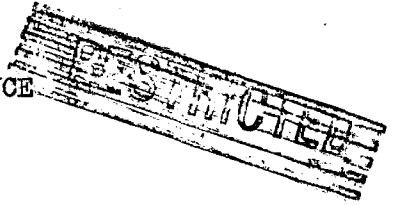
INFORMATION DIVISION
Radiation Laboratory
Univ. of California
Berkeley, California

-3-

MAGNETIC FIELD MEASUREMENTS BY NUCLEAR RESONANCE

Peter Kafitz

August 20, 1948



The purpose of this report is to outline the work done at the Radiation Laboratory toward the development of a magnetic field measuring device using the phenomenon of nuclear resonance. While the work described here is far from complete, it has served to indicate the limitations of the method as well as some of its possibilities. For reasons which will become apparent, the project is being discontinued. It is hoped that this report will serve as a starting point should the work be continued at some later time and that some of the mistakes already made need not be repeated.

Theory

Extensive discussions of the phenomenon of nuclear induction or nuclear resonance are presented in two papers, one by F. Block (Phys. Rev. 70, 460 (1946) and a second by N. Bloembergen, E. M. Purcell, and R. V. Pound (Phys. Rev. 73, 679 (1948)). For purposes of this report the theory may be simplified to the statement that any nucleus, because it possesses a spin and a magnetic moment, behaves in a strong magnetic field as does a gyroscope in a gravitational field. That is, each nucleus precesses about the direction of the applied field with a frequency given by:

$$\nu = \frac{1}{2\pi} \gamma H$$

where γ is the gyromagnetic ratio and H is the applied field. It can be seen that the strength of a magnetic field can be measured by placing in it a small sample of a substance whose γ is known and by some means detecting the frequency of the Larmor precession.

-4-

Our simplified version of the mechanism of nuclear resonance is not complete in that nothing is said of how long such a resonance will persist after the exciting force is removed or how much energy is absorbed in exciting it. These subjects are being investigated very extensively at several laboratories. The reader is referred to the second mentioned paper for a complete discussion of relaxation time effects.

The nuclear moments of a large number of isotopes are known, however, for our purpose, the proton or hydrogen nucleus is the most satisfactory. It has a gyromagnetic ratio which places the Larmor frequency in a range where ordinary radio techniques can be used; that is, for a field of 3000 gauss the resonant frequency is 12.7 megacycles, while for 15,000 gauss it is 63 megacycles. Many materials, water, paraffin, etc., have high concentrations of hydrogen. Water has the additional advantage that various materials can be dissolved in it to affect the relaxation time. The investigation at the Radiation Laboratory was carried out almost exclusively with water or water solutions.

In general there are two ways in which proton resonance can be detected. First, a radio frequency field may be applied to the sample in such a way that the majority of the protons are precessing in phase and their resulting field detected. It is necessary to separate the driving field from the signal field since they are of the same frequency. The former is roughly 10^6 greater than the latter. This can be done by geometry, as in Bloch's method, or by time separation. The second way of detecting proton resonance is by measuring the energy absorbed by a sample. At the Larmor frequency there will be a sharp increase in absorbed energy, provided saturation effects are taken care of. This is the bridge method.

In reality then, there are three methods; Bloch's, time separation, and the bridge method. These were investigated and will be the subject of this report.

Tests in General

For purposes of these tests, it was necessary to have a convenient, stable magnetic field. Since there was no large electromagnet available, we had to be content with a three-inch magnetron magnet. It was found early that the field in the gap was not uniform, so that it was necessary to add soft iron pole faces which were accurately spaced and held parallel by a brass collar. Flip coil measurements showed that the field at the center was 3140 gauss. This put the proton resonance at about 13.4 megacycles. A horizontal check of the uniformity showed that within one fourth of an inch of the center of the pole face, the field was uniform to ± 1 gauss. All the work at the Radiation Laboratory was done with this magnet.

Because 13.4 m.c. is close to the twenty meter amateur radio band and because of the high interference level generally prevailing at the Radiation Laboratory, it was necessary to shield all equipment carefully. Rather than build well regulated power supplies, all the equipment was battery operated. The batteries were also placed in shielded boxes. Even with these precautions the most troublesome problem was separating the desired signal from stray external signals and noise.

In order to separate the proton signal from the background, it is necessary to modulate it in some way. Since the Larmor frequency is proportional to the magnetic field, it is very easy to frequency modulate the proton signal by superimposing a small alternating component of magnetic field upon the steady field of the magnet. If the output of the detector is presented on an oscilloscope whose sweep is synchronized with the modulating field, a pip will appear on the trace each time the proton frequency is swept through the tuned frequency of the detector. By tuning the detector the pip can be moved until it corresponds to the point where the modulating field passes through zero (assuming it

-6-

is sinusoidal). The detector is now tuned to the Larmor frequency of the proton in the steady field and, from this, the value of the magnetic field can be calculated.

In order that the proton resonance can be found easily, a modulating field of at least 25 gauss is desirable. For convenience, the modulating frequency was chosen to be 60 cycles. This choice also had the advantage that, when the output was presented on an oscilloscope, any stray pickup, which is usually 60 cycle, appeared stationary. Because the pole faces of the magnet were not laminated, it was found necessary to create the modulating field by a small coil placed close around the sample within the magnet gap. For shielding the sample and r.f. assembly were placed in a small brass box. The modulating coil was wound outside of this (see Fig. 1). The shield can, of course, reduced the 60 cycle field; however, measurements showed that this was not serious so in the interests of good r.f. shielding, the can was not slotted. Eddy currents in the can caused it to become hot after long use, which might be objectionable in a continuously operating device.

Instead of modulating the proton frequency, the same effect could be achieved by modulating the frequency of the detector circuit. Since this usually involves a number of tuned circuits, the former method seemed more practical for experimental purposes.

As was mentioned, most of the samples were either pure water or solutions. The most convenient method of handling the samples was to seal off 1/2 or 1 cc. volumes in small spherical vials. These were held in place in the coils by simply packing glass wool around them. Several attempts were made to make sample holders of polystyrene, but these were unsatisfactory when the equipment became overheated.

-7-

When it was necessary to measure the r.f. field applied to the sample, the glass holder was removed and a small coil of known area installed in its place. The induced voltage was then measured by a Hewlett Packard, #410A, voltmeter, and the field calculated from well known relations.

Figure 2 shows one other device that proved to be very useful, a sweep separator and phase control for the oscilloscope. This device separated the front and back trace on the screen and made it possible to correct for any phase differences between the sweep and the modulating field.

Nuclear Induction Method

The equipment and procedure used in the investigation of the nuclear induction method is essentially the same as that described by Bloch, Hansen, and Packard (Phys. Rev. 70, 474 (1946)). Figure 3 is a block diagram of the setup used at the Radiation Laboratory. Because of its intended use the circuit was designed so that the pickup head could be removed some distance from the rest of the equipment.

From the above report it was believed that an r.f. driving field of from 5 to 10 gauss was necessary to excite the Larmor resonance. It was later found that 1/2 gauss or even less was sufficient (this was later confirmed by Packard). For this reason the oscillator, shown in Figure 4, was designed to deliver 100 or so volts to the driving coil. Although overpowerful, this circuit operated satisfactorily. In light of the later knowledge, a much smaller unit could have been used.

The receiver, Figure 5, was essentially a crystal diode with low pass filter followed by two stages of pentode amplification. In line with the policy of keeping the equipment simple, the receiver was untuned. Measurements showed it to have a sensitivity of 0.1 millivolts when working into a DuMond, #208B, oscilloscope. From Bloch's paper, this was believed to be adequate; however,

-8-

later work indicated that another factor of ten would have been handy. This would have necessitated tuning the input stage to improve the signal to noise ratio.

The modulator was simply a 6 volt filament transformer, controlled by a Variac. The output was applied to both the modulating coil and the horizontal sweep of the 'scope.

The pickup head is, of course, the most critical part of the equipment. A number were tried, starting with the most simple and proceeding to the more complicated. None was really a success. As was mentioned earlier, it is necessary to eliminate any direct coupling between the driving and pickup coils. There are two reasons for this. First, the driving signal is greater by a factor of 10^6 than the expected signal from the sample, so that any slight variations in the oscillator or noise in the tube will completely swamp the proton signal. Second, the proton signal, while the same frequency as the driving signal, lags it in phase by 90° . As seen by the vector diagrams of Figure 6, unless the proton signal is large compared to the leakage, phase modulation results which is not detected by a simple crystal diode.

A simple geometrical balancing system, Figure 7a, was tried first. Because of the accuracy necessary, this was not practical. It was possible to obtain a balance, but the slightest movement completely upset the adjustment.

A much better arrangement is that shown in Figure 7b. This is the system used by Bloch, Hansen, and Packard. A small semicircular piece of copper, called a paddle, placed near the pickup coil causes a controllable amount of the driving flux to thread the pickup coil. Bloch, Hansen, and Packard give a complete discussion of the operation in their paper mentioned earlier. This device worked reasonably well as long as the operating frequen-

-9-

cy was not shifted. The fact that such a balance is frequency sensitive is not surprising since there undoubtedly exists capacitive as well as inductive coupling between the two coils.

Because of the difficulty in balancing out the leakage flux, it was decided that this method was not suited to our immediate problem, that is, the design of an all purpose magnetometer. No satisfactory results were obtained, although a large part of the blame for this might be laid to the magnet which had not yet been equipped with the special pole pieces.

Further work should take the direction of finding a more suitable means of balancing out the leakage flux. This might be done by artificially adding to the receiver input a small signal from the transmitter of exactly the correct amplitude and phase to cancel the leakage signal.

Bridge Method

The second of the methods investigated was the bridge method. The block diagram of the equipment is shown in Figure 8. In theory this is perhaps the simplest of the three methods. The sample is placed in a coil in one arm of an r.f. bridge. When the oscillator is tuned to the resonant frequency of the protons of the sample, a slight unbalance results due to the absorption of energy by the protons. This unbalance results in a small r.f. voltage appearing at A which is amplified, rectified, and put on the screen of an oscilloscope as before. The principal advantage of this method is that the driving signal is balanced out electrically so that, although the balance is still frequency sensitive, rebalance is achieved by simply adjusting a variable condenser. Also absolute balance is not necessary or even desired, hence a fairly large frequency shift can be made without losing the signal.

The main requirements of the oscillator are that it be reasonably stable

-10-

and that it produce the required field to excite the proton resonance. The oscillator shown in Figure 9 proved to be very satisfactory. A type 6AS7-G is a twin, low mu, triode, which as used here has a gain of less than 2. The low gain makes it possible to drive the grid of one section directly from the plate of the other. The bridge itself forms the tank circuit of the oscillator.

Figure 10 is the schematic diagram of the bridge circuit. It is a conventional radio frequency bridge with both capacitive and resistive balance. The double balancing condenser is arranged so that equal capacities are added and subtracted from opposite arms. Since these capacities are in series and since they form only a small part of the total capacity of the tank circuit, balancing the bridge does not affect the frequency of the oscillator to any great extent.

If pure water is used for the sample, the unbalance at resonance will be strong for about a second after the oscillator is turned on, and then it will quickly disappear. This effect is due to saturation; that is, in a very short time all the protons are lined up and no more energy can be absorbed. The addition of impurities to the water, particularly ferromagnetic salts, shortens the relaxation time so that a continual supply of r.f. energy is necessary to maintain resonance. It was found that the addition of MnSO_4 greatly increased the signal from the bridge. Above concentrations of 0.01 molar, however, there was no further increase in signal.

The signal from the bridge was of the order of 50 microvolts. In order to get the necessary amplification and low noise level, it was necessary to add one stage of tuned r.f. amplification to the receiver previously used. The complete circuit is given in Figure 11.

The results obtained with the bridge method as described here were

-11-

quite satisfactory. A recognizable proton signal could be obtained under the worst conditions of background noise. Under better conditions, a signal of roughly twenty times the height of the "grass" was the rule. One very serious limitation was encountered. As the sample was moved to portions of the air gap where the field was slightly more non-uniform, the signal rapidly broadened and disappeared. At non-uniformities of the order of 3 gauss (out of 3140) over the width of the sample the signal was barely recognizable.

This difficulty is inherent in any method using proton resonance, and it is the main reason for not proceeding with the program.

Time Separation Method

The time separation method will be described only briefly since it was completely unsuccessful. The basis for this method is the fact that the relaxation time of protons in pure water is known to be greater than several seconds. It was hoped that it would be possible by using a gated oscillator and receiver to excite the resonance, cut off the driving signal and cut on the receiver, and to pick up the signal from the still spinning protons. In this way the interference from the driving signal could be completely eliminated without using any balancing system. The gating could be synchronized with the sweep, so that on alternate half cycles the sample would be re-excited.

It was realized at the start of this investigation that such a scheme would not work in anything but an extremely uniform field unless some sort of coupling existed between the individual protons which would keep them in phase with one another after the driving field was removed. If no such coupling exists, a few simple mathematics will show that two protons which find themselves in fields differing by one gauss out of 3000 will be 180° out of phase after about 100 microseconds. Thus, if the field over the sample varies one gauss, there will be phase persistence for only about this length of time.

-12-

This is too small a fraction of a 60 cycle, or even a 500 cycle, sweep to detect the resonance.

Our investigation indicates that there isn't sufficient phase persistence to make the method practical. Figure 12 shows the experimental setup. The oscillator is very similar to that used in the bridge method except that it was gated by driving the grids negative to cut off. The receiver was a superhetrodyne with two stages of i.f. amplification. It was gated by a signal applied to the suppresser grid of the local oscillator which cut the tube off. Tests with a General Radio signal generator showed the receiver to have a sensitivity of better than 25 microvolts at the grid of the mixer tube. Ahead of this was a tuned circuit with a Q of about 40, so that the overall sensitivity was certainly better than 10 microvolts. No proton resonance could be detected although the position of the resonance was known from measurements using the bridge method.

This method would probably work in an extremely uniform field; however, this requirement makes it impractical for a general magnetic field measuring device.

General Conclusions

This investigation into the possibility of using the Larmor precession of the proton in a magnetic field to measure that magnetic field has indicated that while there are methods which will work and work well, they require equipment which is somewhat difficult to use. For applications where the field is uniform and where accuracy rather than speed and ease of measurement is required, a method using proton resonance is ideal. The bridge method and (on the basis of the success at Stanford) the nuclear induction method are well suited to monitoring a known field or, with a little ingenuity, regulating such

-13-

a field. Both give continuous readings, which is not true of flip coils.

Because it is necessary to make a number of fairly precise adjustments for each value of field determined, none of the proton methods is suited to field mapping or general field measuring applications.

The work described in this paper was performed under the auspices of the Atomic Energy Commission.

LMB/9-23-48
Information Division

FIGURE 1

Sketch of Pickup Head Showing Modulating Coil, R.F. Coil,
and Sample

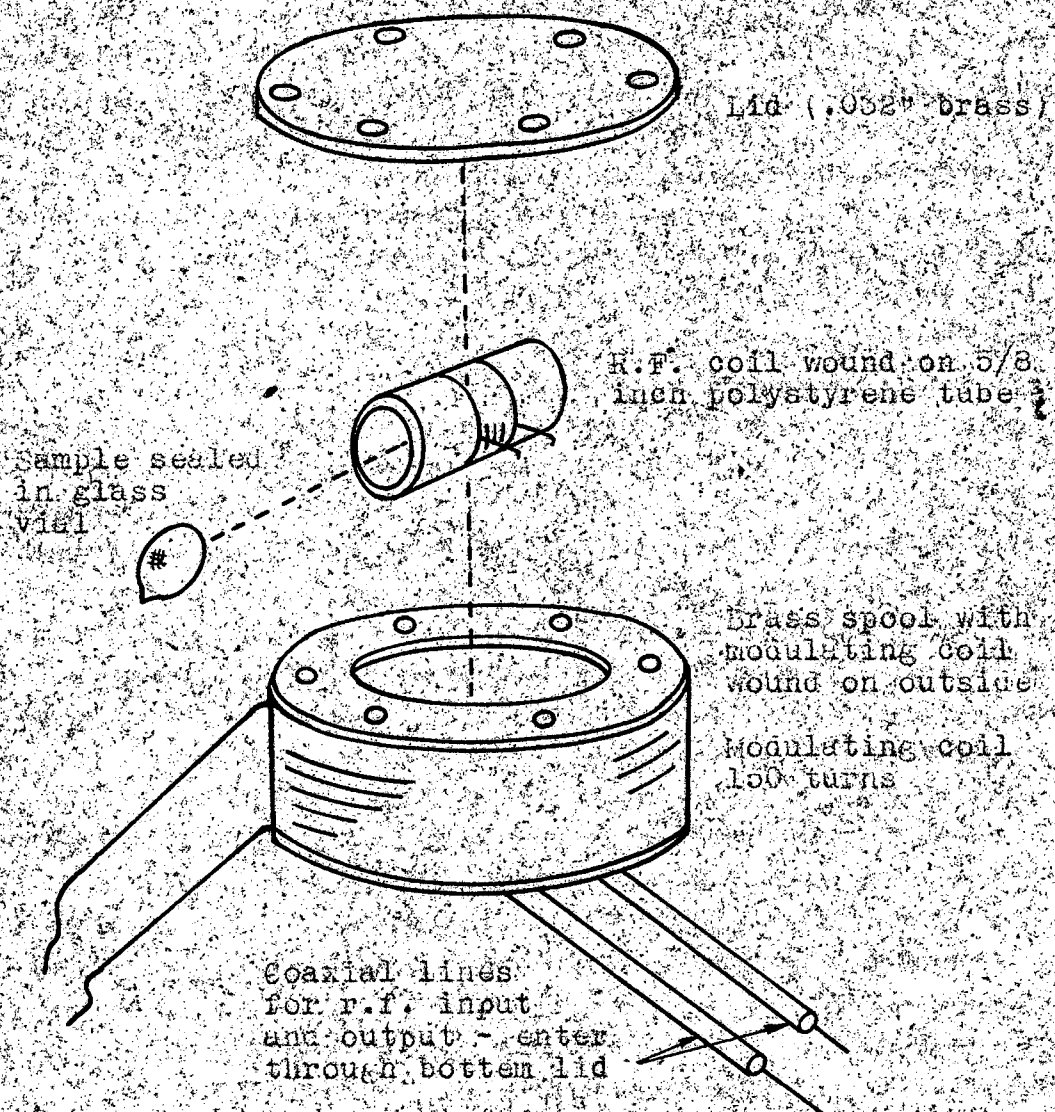


FIGURE 2

Sweep Separation Circuit

Trace on 'scope

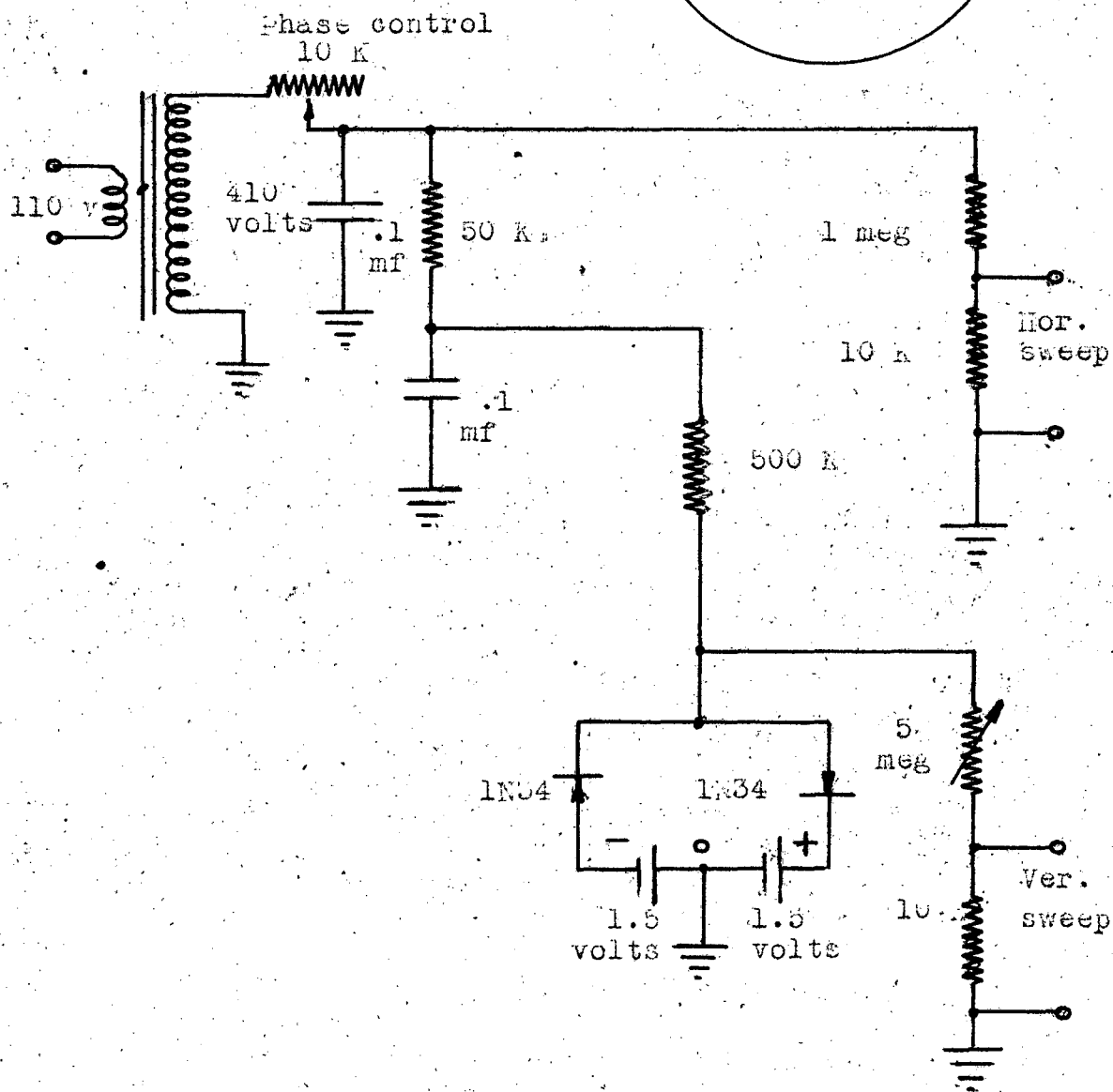
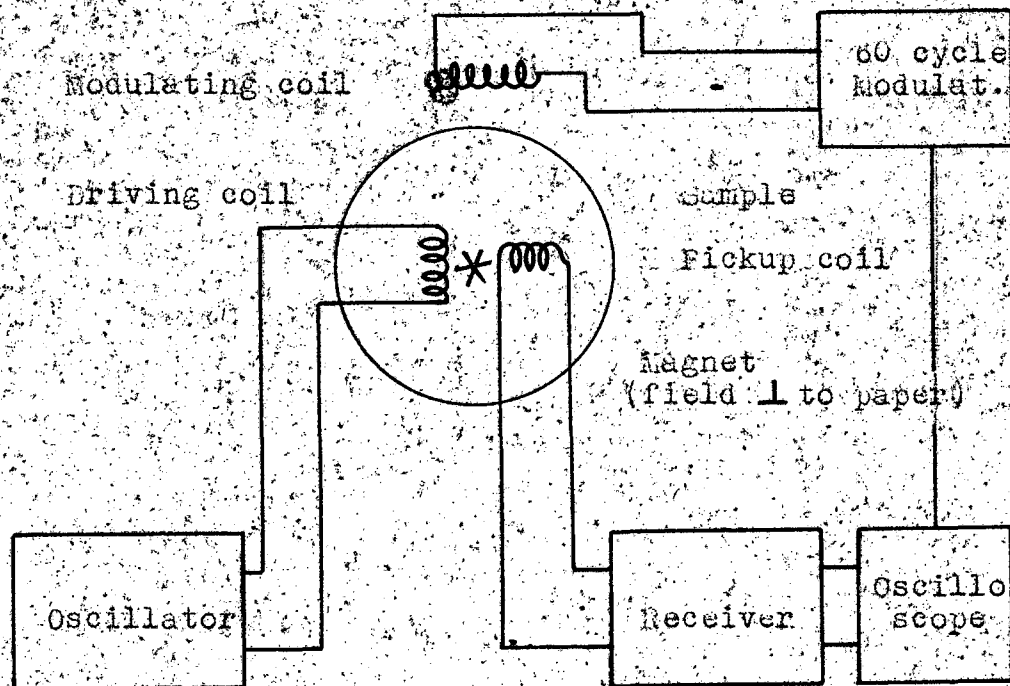


FIGURE 3

Block Diagram of Nuclear Induction Method



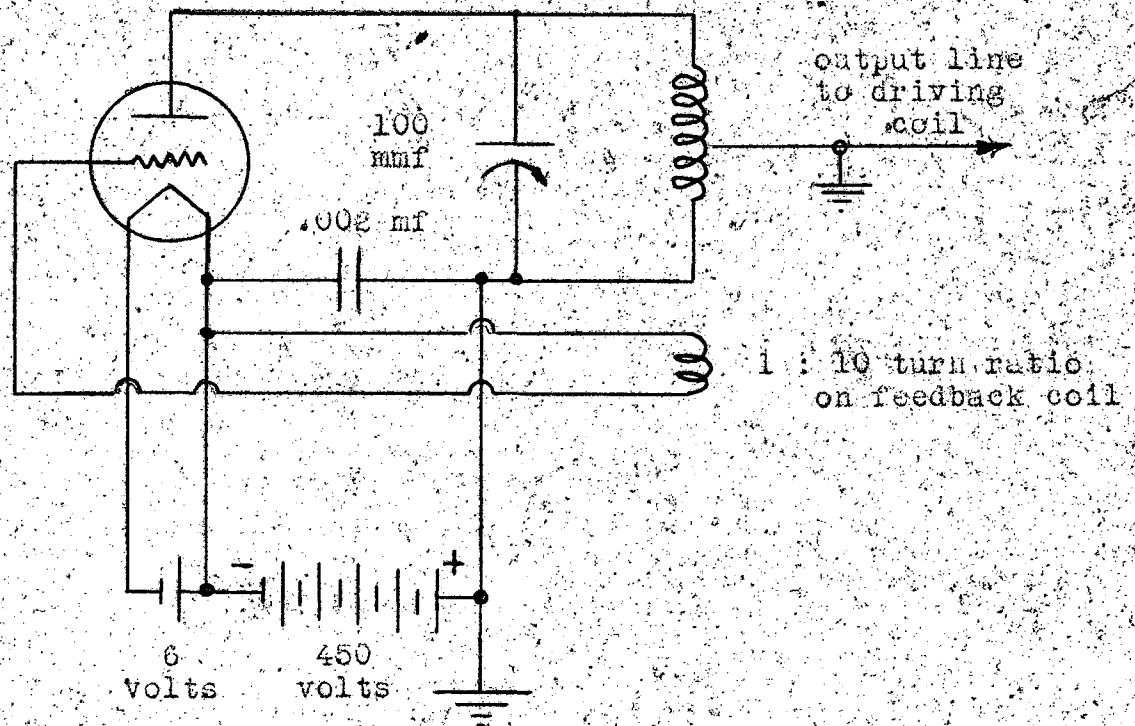
Driving and pickup coils are so arranged that there is no direct coupling between the two.

60-cycle modulation frequency is also applied to the horizontal sweep of the oscilloscope.

FIGURE 4

Circuit Diagram of Oscillator

3imaac 35TC



Receiver Circuit for Nuclear Induction Method

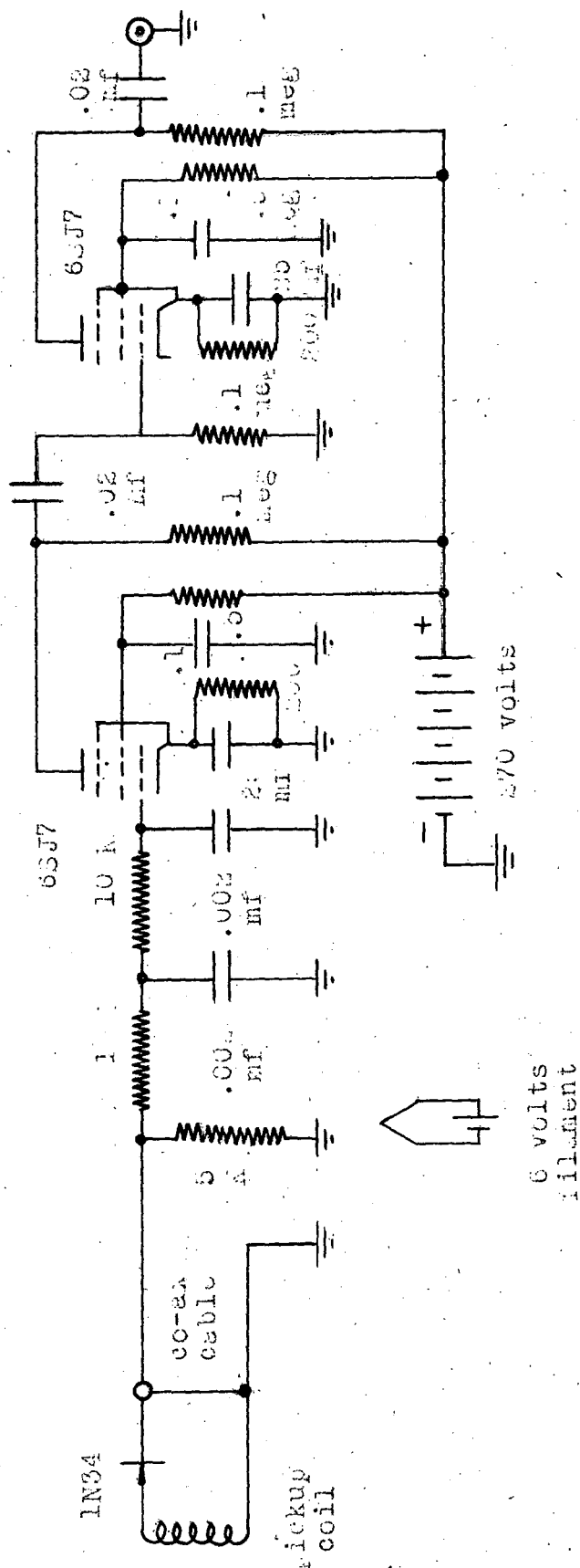
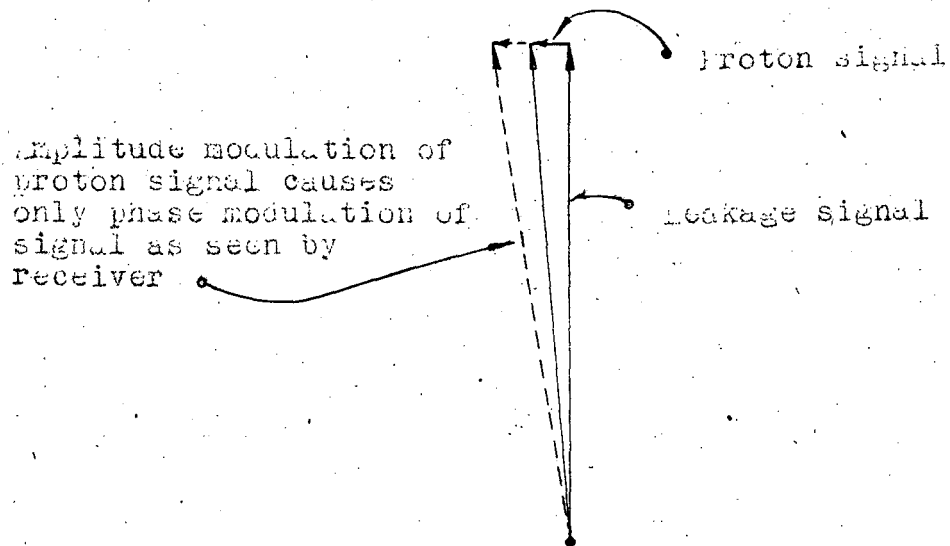


FIGURE 6

Vector Diagrams Showing Effect of Leakage Signal

Leakage signal large compared to proton signal



Leakage signal smaller than proton signal

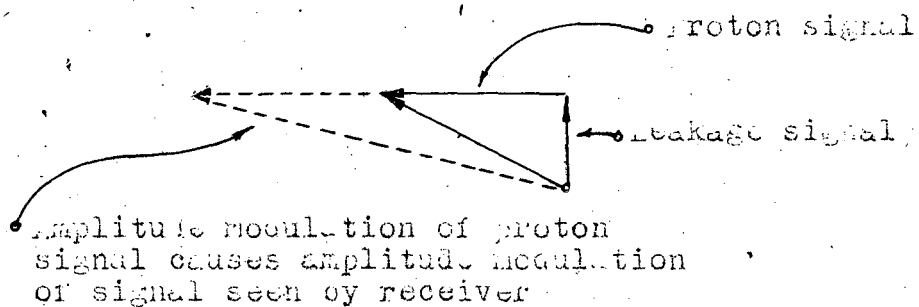
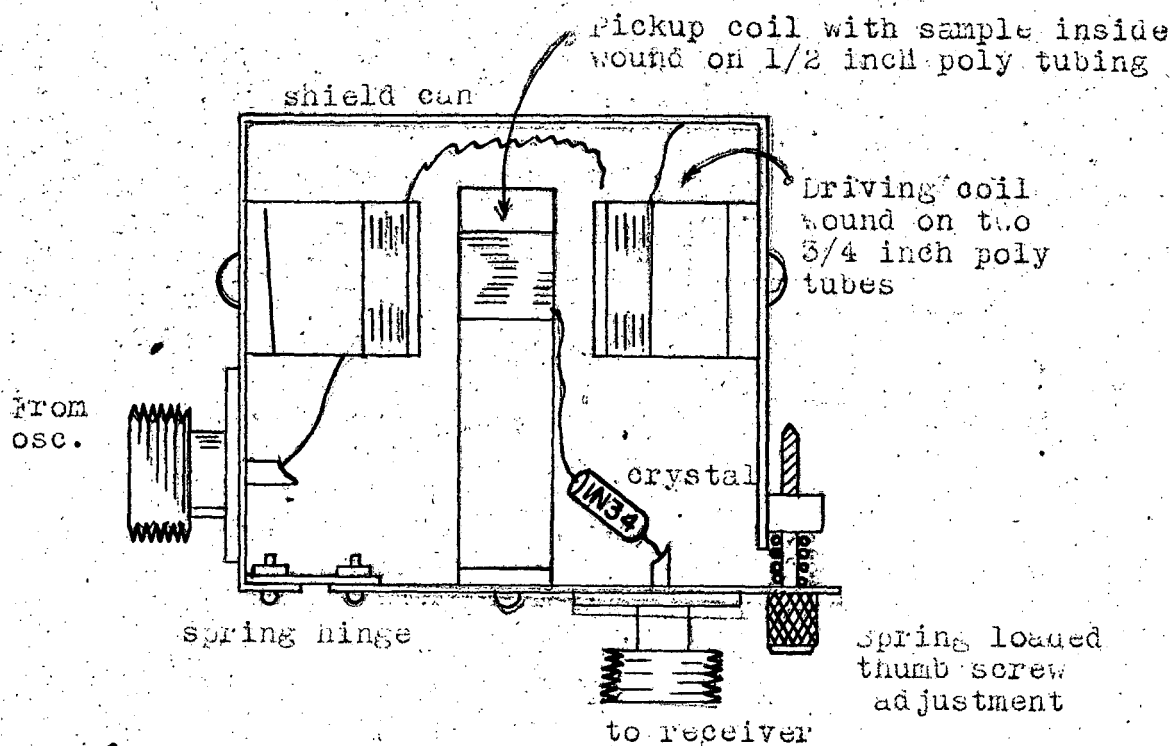


FIGURE 7

Geometrical Balanced Coils



Paddle Balanced Coils

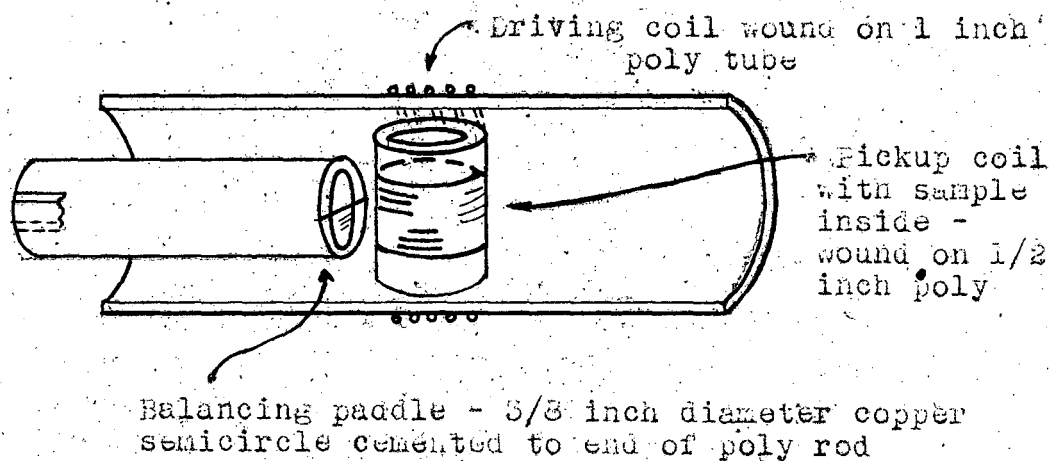


FIGURE 3

Block diagram of bridge method

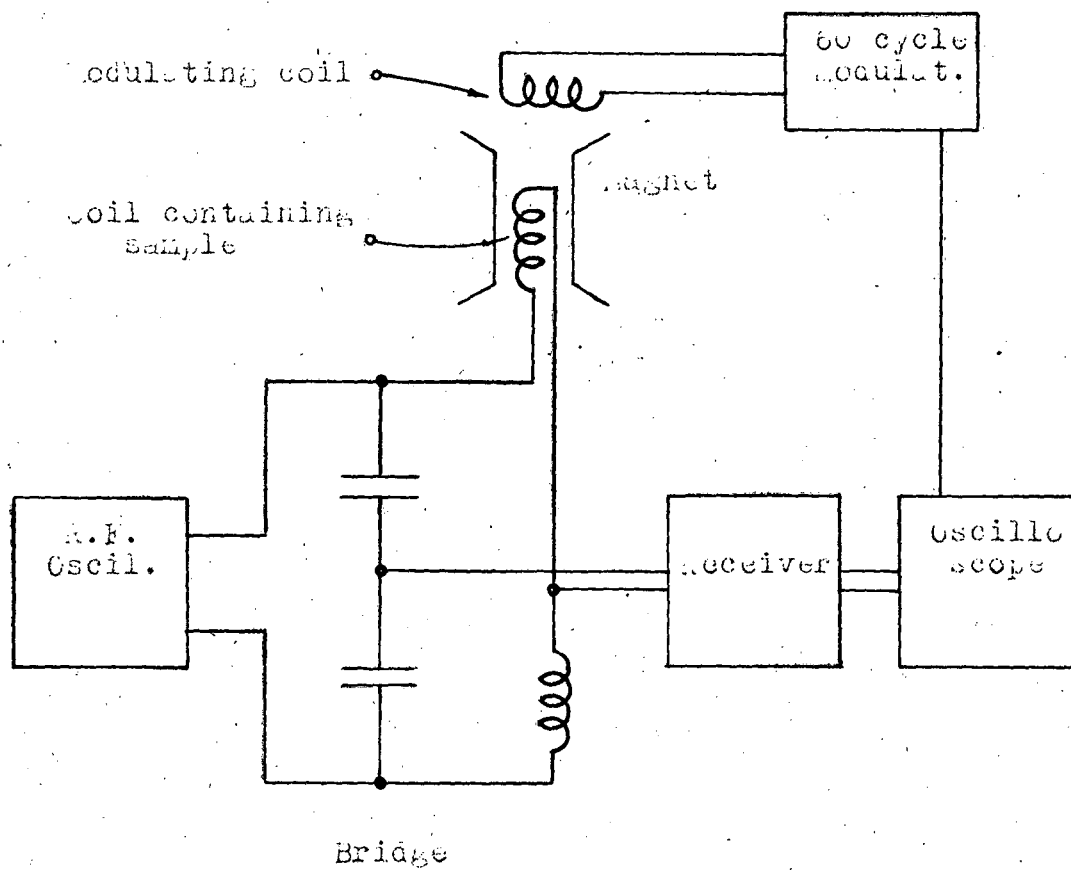


FIGURE 9

Oscillator for Bridge Method

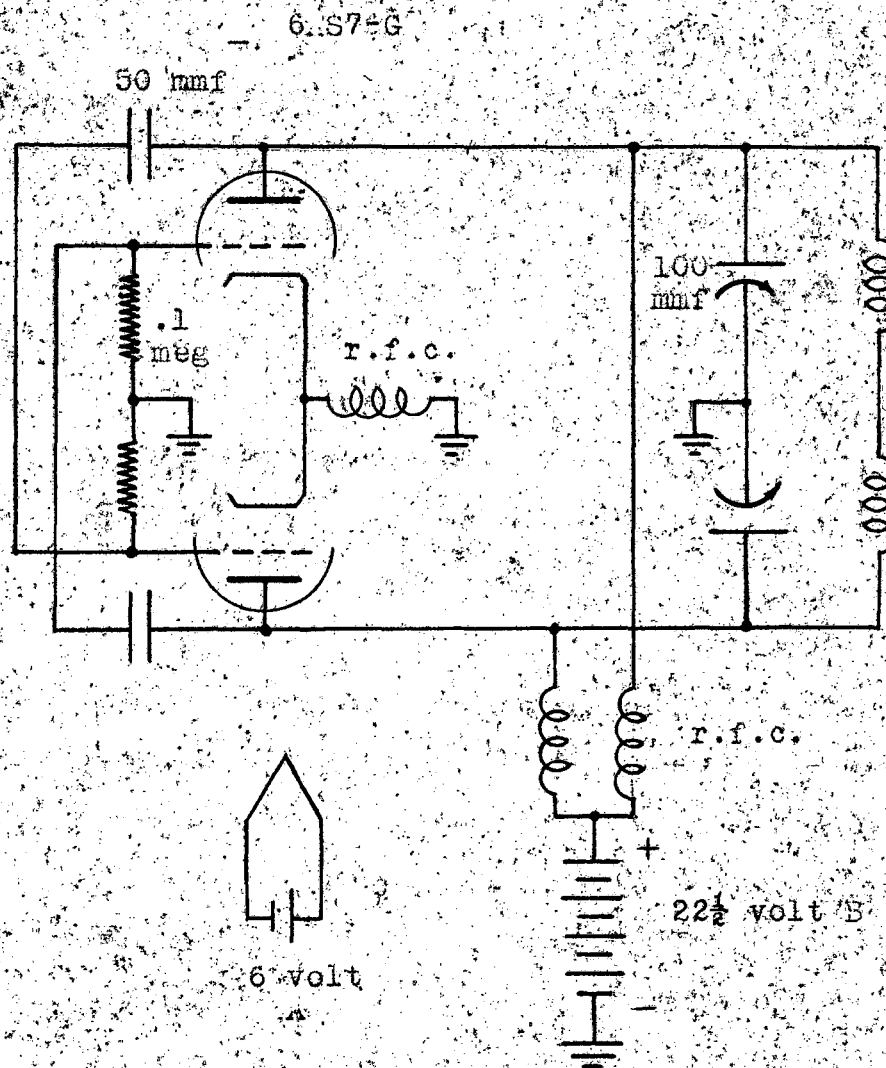
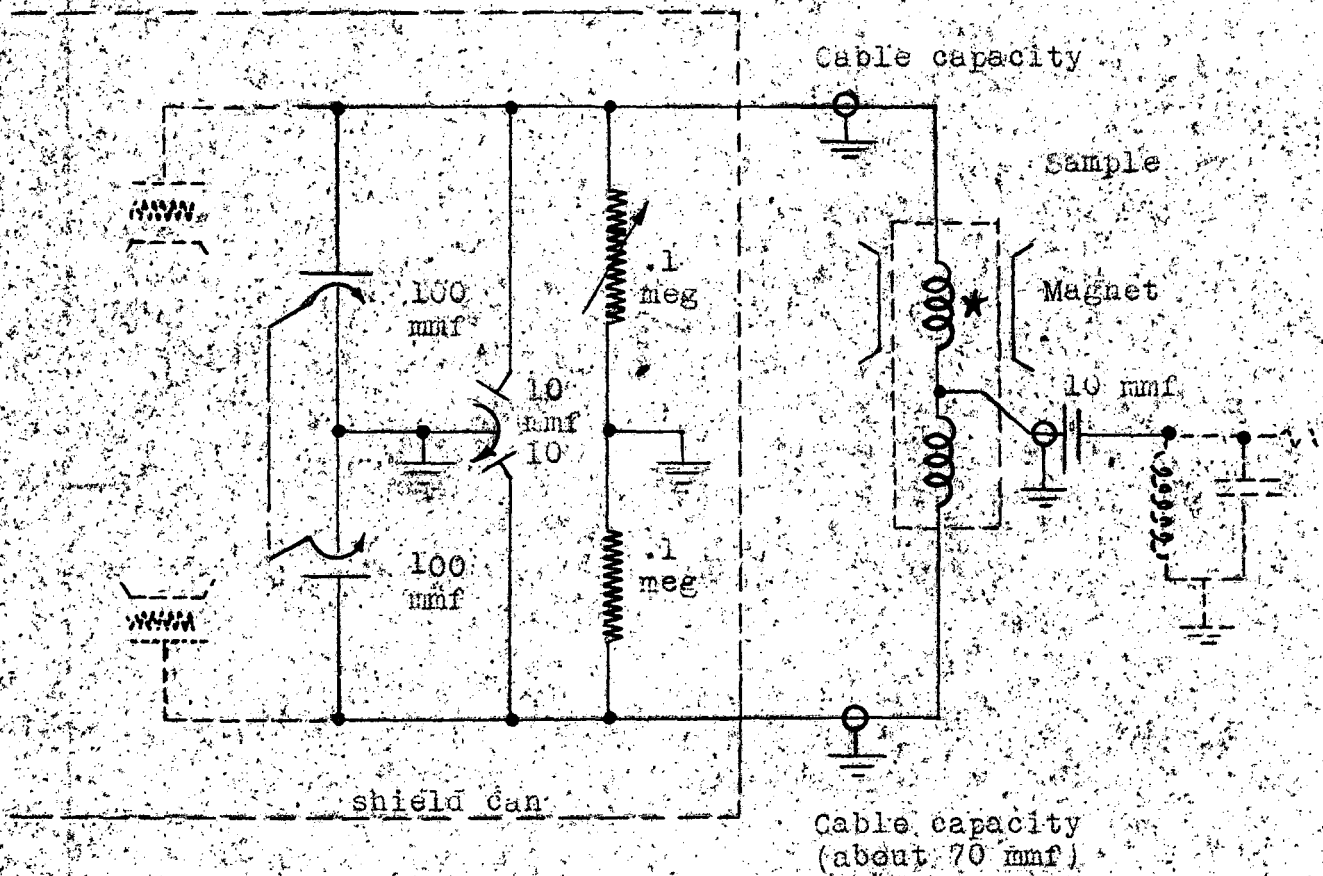


FIGURE 10

Bridge circuit



Tuning cond.

Balance resistors.

Balance cond.

Bridge coils: 10 to 14 turns close wound on 3/4 inch polystyrene tube.

Receiver Circuit

FIGURE 11

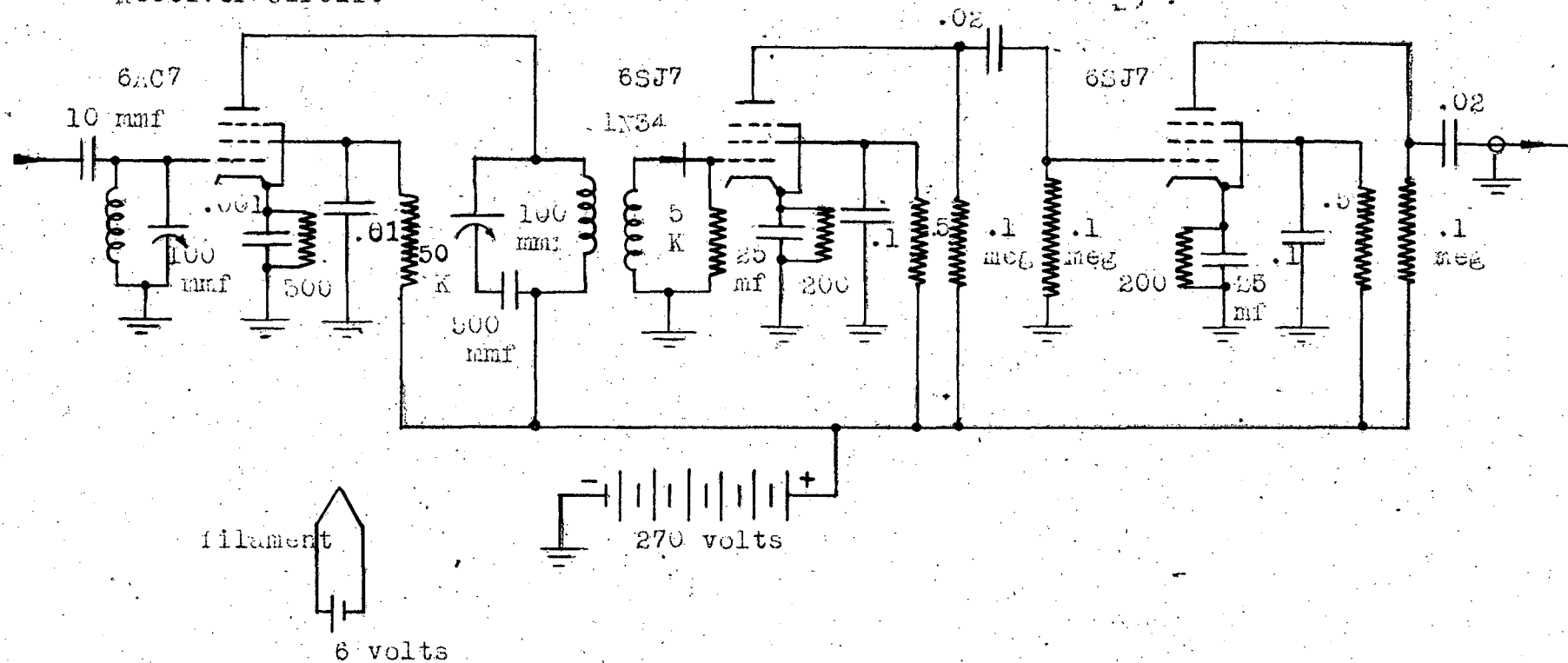
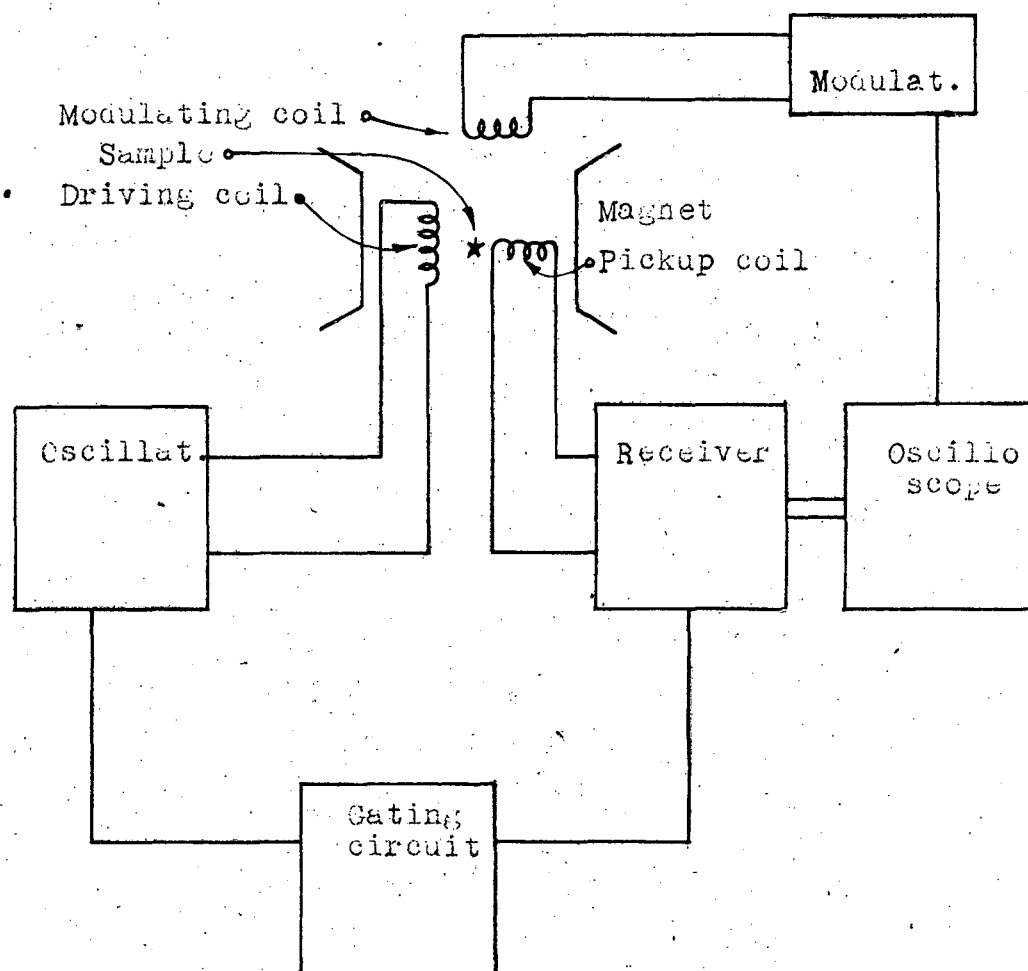


FIGURE 12

Block Diagram of Time Separation Method



The driving and pickup coils are placed at right angles to one another so that the tuned input of the receiver will not load the oscillator. Both are at right angles to the magnetic field.

RESTRICTED