A MAGNETOMETER FOR MEASURING FIELDS TO 300 GAUSS

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ABSTRACT

This instrument was developed for measurement of magnetic field in an electron cyclotron where the following requirements were to be met:

(a) accuracy of 0.1% to fields of 100 gauss;
(b) continuous monitoring of magnetic field to allow automatic plotting of field versus position of the probe;
(c) quadrupole probe construction, minimizing the effect of near-by iron on the measurements.

Two newer versions of the probe have been built, one--for measurement of the earth's field--which sacrifices field range above 10 gauss for small size, and the other--for fields to 300 gauss--which sacrifices quadrupole construction.

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Introduction

Many magnets are constructed to have a uniform field over as large an area of the pole pieces as possible. Measuring the magnetic field under these circumstances is a relatively easy matter. However, where the gap may be as small as one-half inch, and where the magnetic field must agree both radially and circumferentially with mathematically determined values, as for example in a small electron cyclotron, magnetic measurements can be very tedious.

The magnetometer described here, developed to make continuous magnetic measurements in such a cyclotron, had to meet the following requirements:

(a) Accuracy of 0.1% in fields of 10 to 100 gauss

(b) Continuous monitoring of magnetic field to follow automatic plotting of field versus position of the probe

(c) Horizontal position accuracy of approximately 0.005 in.

(d) Quadrupole probe construction to minimize the effect of near-by iron.

This instrument consists essentially of two parts, the sensing probe which detects the magnetic field, and an electronic chassis which is necessary to make it operate.

Sensing Probe

The sensing probe for this instrument is a small, carefully constructed transformer consisting of three windings with a 0.001-by 0.005-by 0.250-in. Permalloy strip as a core. Figure 1 shows the construction of the probe and the electrical connections of its windings. The core is accurately centered in a lucite spool on which ten layers of No. 40 Formvex-covered copper wire are wound, with polystyrene sheets as spacers between layers. The primary of the probe consists of the two outer layers and the four inner layers; the four intermediate layers serve as a secondary for the transformer. The mean diameter of the four inner layers is approximately $1/\sqrt{2}$ of the mean diameter of the outer two layers. Thus, the area of the inner winding is approximately the same as the area between the outer and inner winding, and when the two windings are connected so that current flows in the opposite direction in the two windings, the primary acts as a magnetic quadrupole causing the magnetic field in the region around the probe to fall off much more rapidly than it would with a single coil. This helps to isolate the probe from nearby magnetic material but reduces the total number of ampere-turns acting on the magnetic core to 1/3 of what it would be if the inner and outer windings were connected series-aiding. When in use there is a small amount of radiofrequency current and a relatively large amount of direct current flowing in the primary windings of the probe. The total effective ampere turns of the primary determine the maximum range of the instrument, so it is desirable to make this as large as possible consistent with the necessarily small size of the coil. An arbitrary limit of 300 ma was chosen, with No. 40 wire and Dow Corning silicone compound X2452 conducting heat to a split copper heat sink surrounding the coil. At this current, the lucite core is approaching the softening temperature, and the maximum field that can be measured is about 100 gauss.

The first probes made had fins for convection cooling of the heat sink. Several probes were made at a later time, one for measurement of earth's magnetic field in a 0.5-in.-diameter tube. This probe had a maximum rating of 10 gauss or 30 ma, and no heat sink was necessary. A still later version of the probe was made in which the quadrupole construction was sacrificed to obtain a 300 gauss maximum. This probe was for use in a vacuum, and it had a conduction-cooled heat sink. Figure 2 shows from left to right: an unmounted sensing probe, the 10-gauss model, the 100-gauss convection-cooled version, and the 300-gauss conduction-cooled model for use in vacuum.

Principle of Operation

The magnetization curve of the Permalloy core is approximately as shown in Fig. 3. The primary winding is excited with a radiofrequency voltage which is just sufficient to bring the magnetic field to the knee of the magnetization curve. The voltage induced in the secondary winding is rich in harmonics, but because of the symmetry of the magnetization curve, these harmonics are all *odd* *if* there is no d-c magnetic field present. A d-c magnetic field as small as 2 millioersteds causes appreciable amounts of *even* harmonics to be generated. The even harmonics are used to servo direct current through the primary winding in a direction that minimizes the production of even harmonics. This results in a cancellation of the external d-c magnetic field in the region surrounding the Permalloy core. The Permalloy, then, is operating in a region of nearly zero field at all times, and the probe is quite linear, with direct current in the primary winding proportional to external magnetic field. Because of the large length-to-cross-section ratio of the Permalloy, the probe responds to the component of magnetic field parallel to the core.

Electronic Circuits

A block diagram of the magnetometer is shown in Fig. 4. Because of the number of components included in the feedback loop of this system, it is a difficult one to close. In order to avoid excessive phase shift, the filter network and the a-c amplifier were designed to have a phase shift of less than 90 deg. from 225 kc to 425 kc. There are large amounts of first, third, fifth, and seventh harmonics, and a small amount of second harmonic coming from the secondary of the sensing probe. The problem is to amplify only the second-harmonic signal without having excessive phase shift near the second-harmonic frequency. Bridge-tee filters were used as shown in Fig. 5 to accomplish this.

The amplifier shown in Fig. 6 was designed to amplify the second harmonic signal and reject higher harmonics and low-frequency noise. This was accomplished by a low-Q circuit tuned to the second harmonic frequency. The Q was restricted to about ten to avoid too much phase shift. The fourth stage of the amplifier is somewhat unusual in that it is used as a phase detector as well as an amplifier. The plate voltage on this stage consists of a sinusoidal voltage of twice the osc. freq. and of 300-v peak amplitude. This voltage can be adjusted to be in or out of phase with the second-harmonic signal coming from the sensing probe

The tube acts as a shunt rectifier and develops a negative dc plate voltage which is dependent on the second-harmonic grid signal. The fixod bias on the cathode is adjusted so that negative 35 v is developed at the plate with no grid signal. With an in-phase grid signal, the tube conducts more strongly and the rectified plate voltage becomes less negative. Conversely, with an out-of-phase grid signal the rectified plate voltage becomes more negative.

This rectified plate voltage is applied to the grids of four 6L6's in parallel, which serve as series regulator tubes to control bias current in the search coil. A bridge-tee filter tuned to the second-harmonic was necessary at this point to attenuate the 325-kc 300-v signal applied to the amplifier plate. In addition there is a shunt capacitor which, together with the source impedance of the rectifier, serves both as a filter and as the time constant on which the servo loop is closed. It provides most of the phase shift (6 db/octave) out to a frequency (100 kc) where the loop gain is less than one. The total range of voltage on the 6L6 grids can vary from 0 to -100 v, which allows them to control bias current from 300 ma to a few ma. As the 6L6's are cut off, their transconductance becomes smaller. Normally the loop gain of the magnetometer would become lower, until at some current, the accuracy would be less than required. To avoid this, the cathodes of the 6L6's were biased to a negative supply so that 10 ma of current is diverted around the search coil at all times. Thus with no current in the bias winding, corresponding to zero field, the 6L6's still have considerable gain.

Three different shunts were provided to monitor the current through the bias winding. One was for a 1% front-panel meter, and the other two with 0.1% accuracy for use with a Speedomax recorder.

The magnetometer has proved quite reliable and, when carefully adjusted, is capable of giving accuracies to within a few millioersteds throughout its range. Even when it is not carefully adjusted, the instrument measures accurately to 0.1% of full range on the 100-gauss range, which is satisfactory for many applications.

Legends

Fig. 1. Sensing probe. Cross section of probe with dimensions (top), and electrical connections of probe (bottom).

Fig. 2. Search coil and mountings.

Fig. 3. The operating region on the magnetization curve.

Fig. 4. Block diagram of magnetometer.

Fig. 5. Bridge-tee filter circuit.

Fig. 6. Schematic diagram of amplifier and phase detector.

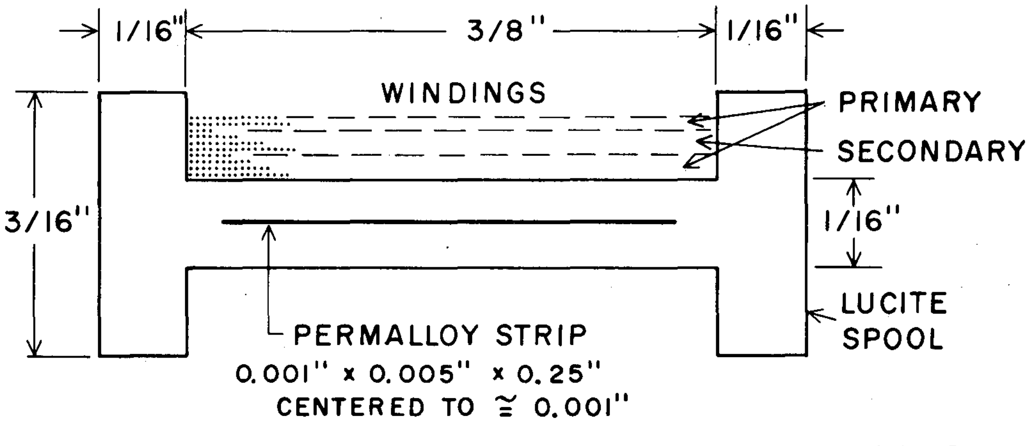

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Fig. 1a

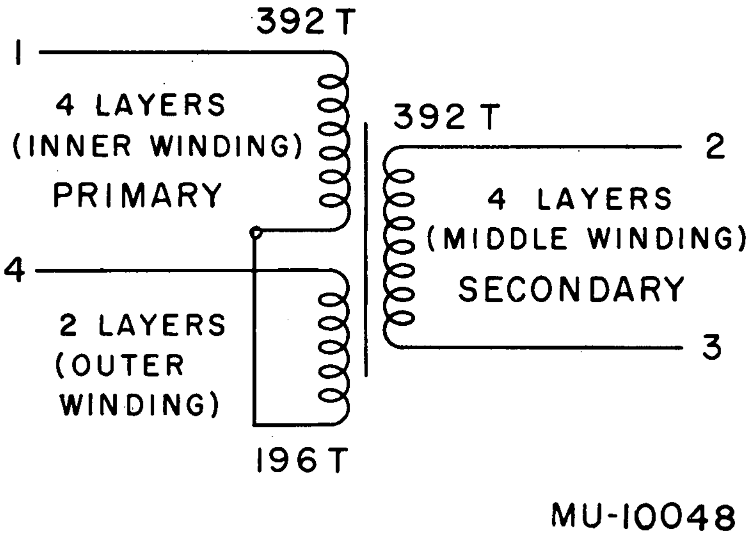
392 T
1
4 LAYERS
(INNER WINDING)
PRIMARY
4
2 LAYERS
(OUTER
WINDING)
196 T
392 T
2
4 LAYERS
(MIDDLE WINDING)
SECONDARY
3
MU-10048

Fig. 1b.

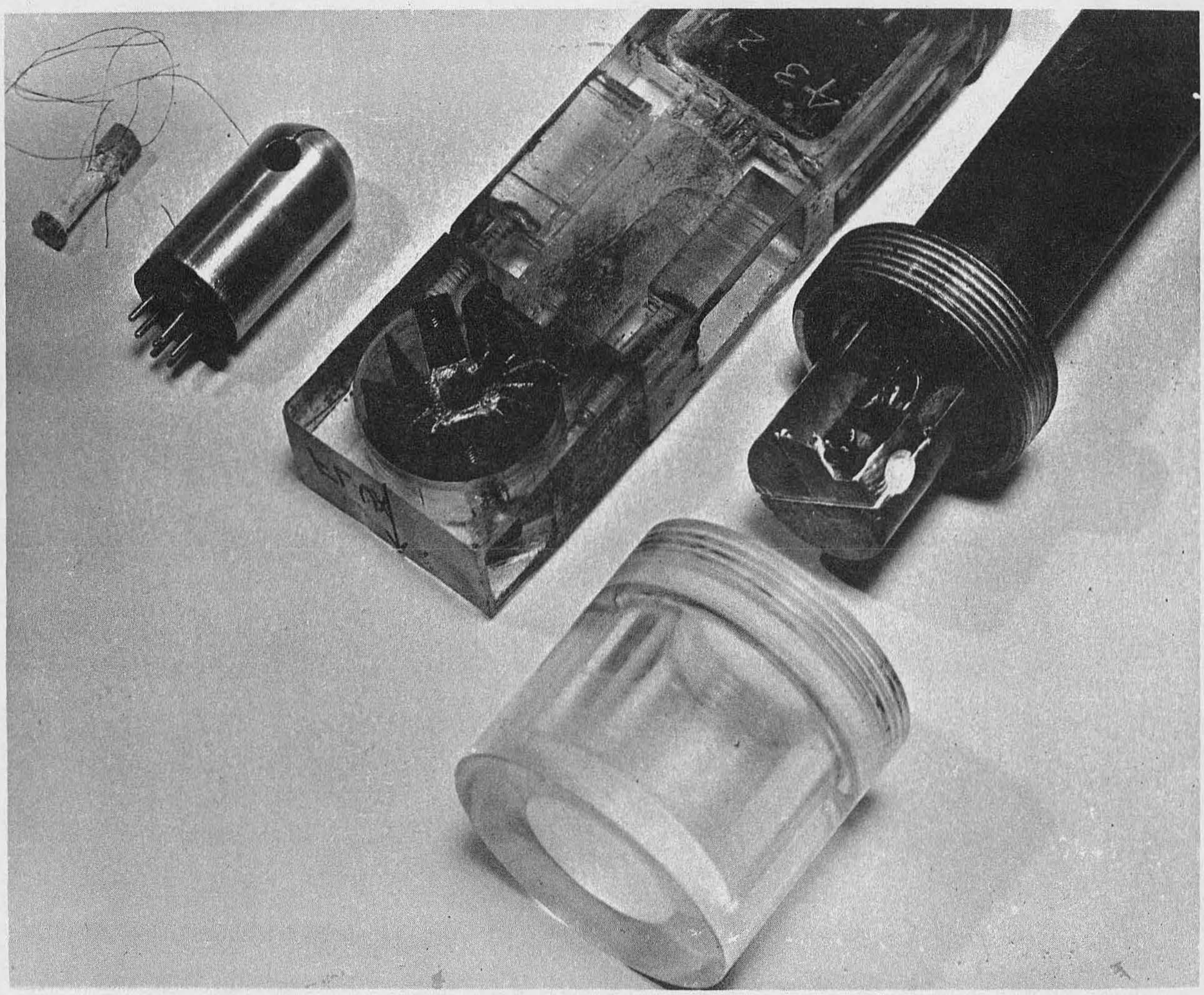

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Fig. 2

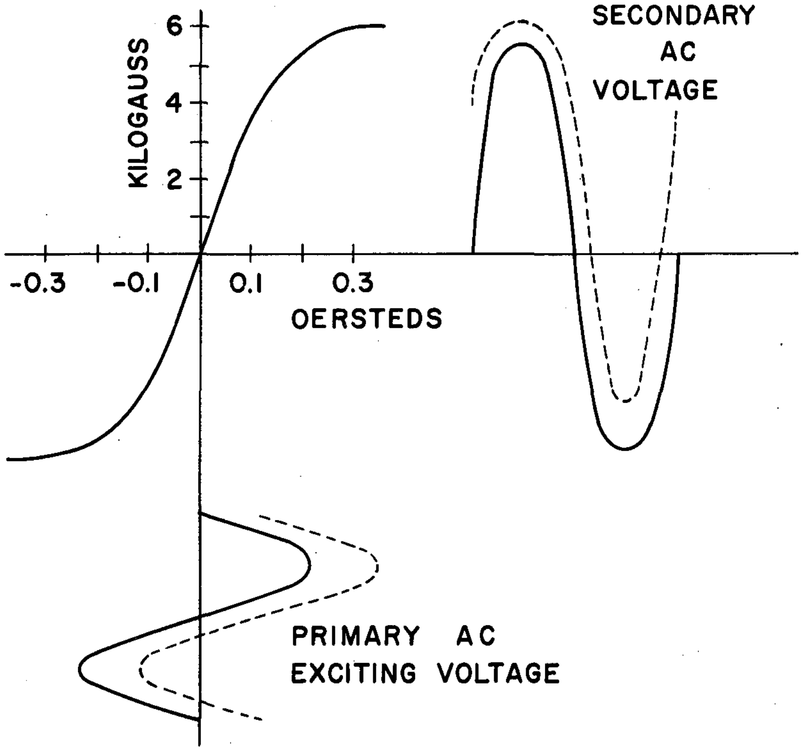

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Fig. 3

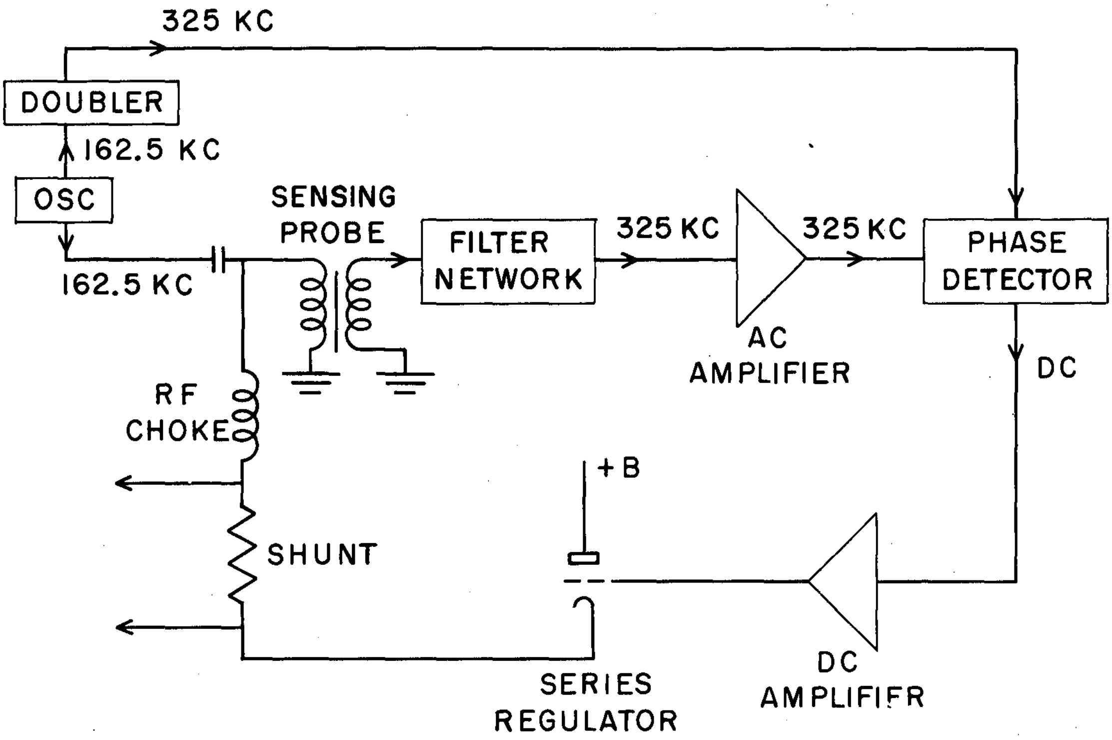

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Fig. 4

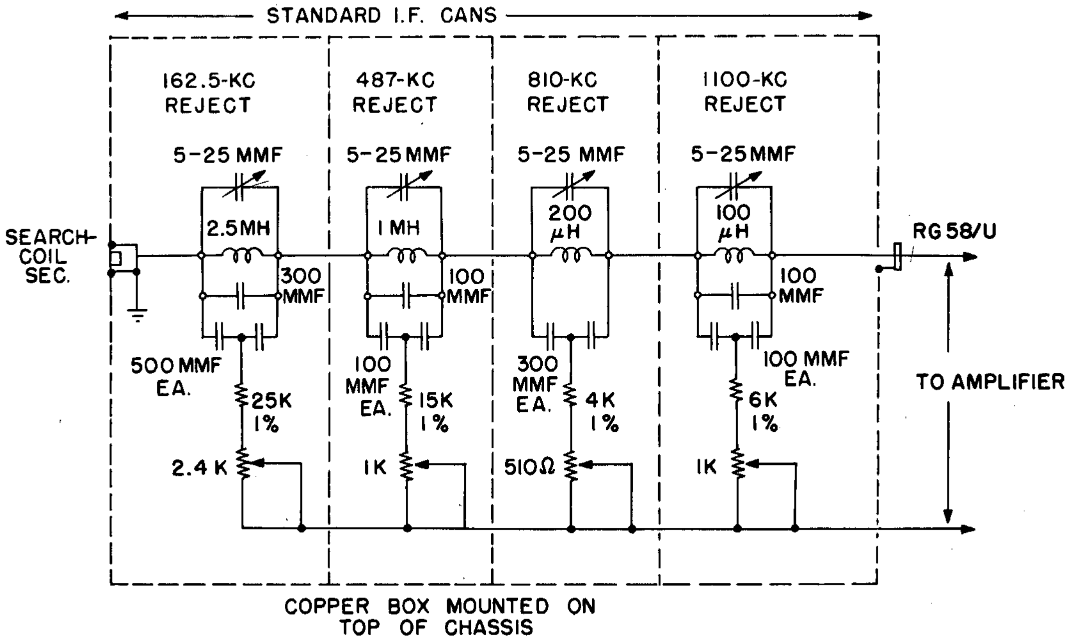

FIG. 5
REJECT FILTER

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Fig. 5

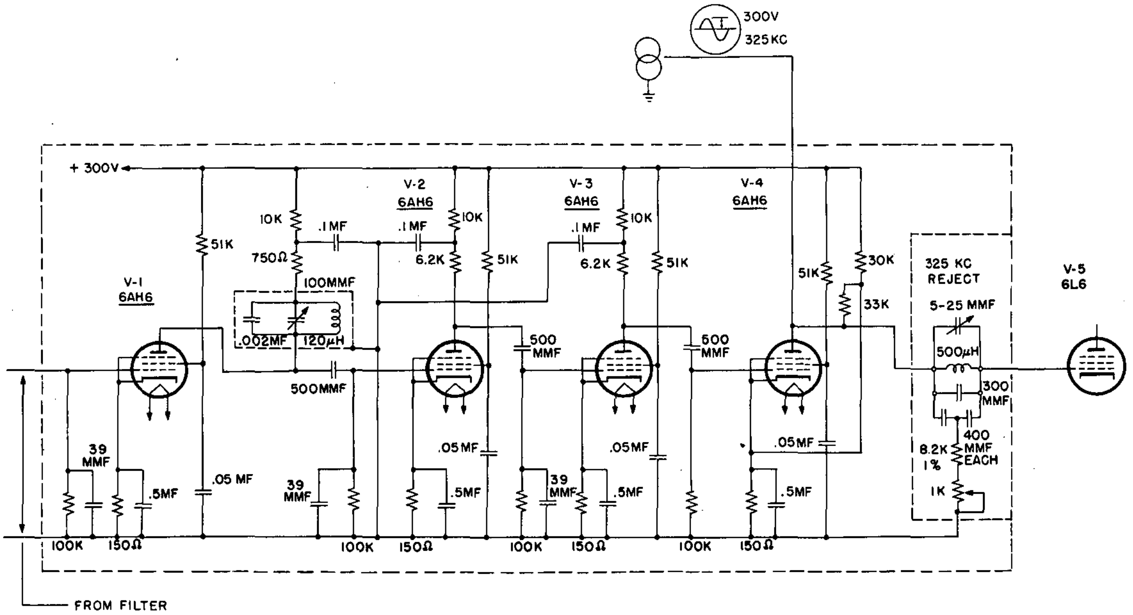

FIG. 6
AMPLIFIER AND PHASE DETECTOR

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Fig. 6