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APPLICATION OF NMR CIRCUIT FOR SUPERCONDUCTING MAGNET USING SIGNAL AVERAGING

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Summary

An NMR circuit was used to measure the absolute field values of Fermilab Energy Doubler magnets up to 44 kG. A signal averaging method to improve the S/N ratio was implemented by means of a Textronix Digital Processing Oscilloscope, followed by the development of an inexpensive microprocessor based system contained in a NIM module. Some of the data obtained from measuring two superconducting dipole magnets is presented.

Introduction

Nuclear magnetic resonance (NMR) techniques are widely used for absolute magnetic field strength calibration of conventional dipole magnets. In this case, field uniformity is determined primarily by the iron pole piece configuration. It is usually more difficult to use an NMR circuit in making field measurements of superconducting dipole magnets because of the higher and less uniform fields involved. Above 20 kG, NMR samples other than proton elements are commonly used to avoid the higher frequencies associated with proton resonance; e.g. lithium, copper and aluminum. The disadvantage in using these elements is the smaller signal at resonance compared to proton elements. To increase the S/N ratio, phase sensitive detection and signal averaging have been used. Signal averaging was employed in our application because phase sensitive detectors require the field to be swept slowly, increasing measurement time.

Recently, it became necessary to develop absolute field measuring equipment for the Energy Doubler dipole magnet project. We needed to know the exact field values relative to current values in order to investigate maximum field values. We also needed to know the effects due to steel saturation and the magnetization characteristics of superconductors. To accomplish this, we used an NMR circuit, initially coupled to a Tektronix Digital Processing Oscilloscope for signal averaging, and measured fields up to 44 kG using proton and lithium samples on a five-foot prototype magnet, E5-1. Recently, a simplified and inexpensive microprocessor system was developed for signal averaging. Using this system with a proton NMR sample, successful measurement of a twenty-two foot magnet was accomplished. The operational characteristics of the methods, the circuits used and the experimental results are to be described.

System Electronics

A. NMR Circuit

The NMR circuit is contained in a 3-wide NIM module and is patterned after the system developed at CERN[1], the major difference being the incorporation of a frequency counter and probe modifications. The NMR, along with the microprocessor signal averager, is shown in Fig. 1. In the foreground is the NMR preamplifier and probe. This circuit uses the "Q-meter" method for detecting resonance; the resonant circuit being automatically tuned to the applied frequency with the aid of a variable capacitance diode. After the signal is observed and the system placed in the lock mode, the system can follow field variations of about ± 200 Gauss. The entire frequency range of the system is from 28 to 91 MHz. The counter provides a readout of the excitation frequency.

B. Signal Averager

Signal averaging techniques have been previously applied to NMR signals[2]. For the present work, the averaging was initially accomplished through the use of a Tektronix Digital Processing Oscilloscope (DPO). Although the signal averaging technique was useful, the DPO system was rather cumbersome to operate and the job did not require the full capability of a PDP-11 computor, which is a part of the DPO. A microprocessor could easily perform the averaging and could be configured as a stand-alone dedicated instrument. The 6800-based system shown in Fig. 2 was configured to provide a 256 point average with 8-bit resolution averaged over a selectable number of scans. It is packaged as a NIM module and includes an input amplifier of variable gain with an 8-bit analog-to-digital converter, the microprocessor and its associated memory, and an 8-bit output digital-to-analog converter.

The analog input signal is connected to the system along with a synchronous interrupt trigger pulse. In response to the interrupt, the microprocessor digitizes 256 points during 20 or 50 ms time periods and accumulates sums of the input data. Another reading of the 256 points is initiated by the trigger pulse, until the pre-selected number of scans has been completed. The sums are then normalized to the number of scans and transferred to a 256 byte output buffer. Data from the output buffer, representing the last averages, are "replayed" through the D-to-A converter for display on an oscilloscope. An output sweep is generated following each digitizing sequence to provide a live display of the averaged signal. The output buffer is updated after the pre-selected number of scans have been averaged, and the entire process is repeated. The flow chart of this operation is given in Fig. 3.

The system described here requires less than 1 k of read-write data memory (RAM) and ½ k of programable read-only memory (PROM). Approximately two man months were required to assemble the hardware and provide the software for this application.

Characteristics

A very clean proton signal can be observed for homogeneous magnetic fields between 6.6 and 21.4 kG, 500 mv to 2v respectively. The lithium (^{7}Li) signal (17∼55 kG) is considerably weaker; even in a very homogeneous field, signal level is typically 150 mv. When used in a superconducting magnet with worse field characteristics, it becomes essential to utilize signal averaging. The sample used was a saturated solution of LiCl with $CuSO_4$ added to provide paramagnetic ions. Field homogeneity is an important factor in obtaining a

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clear signal. At high fields, the absolute inhomogeneity over the sample volume gets quite large and causes a widening of the line width and a corresponding decrease in the S/N ratio. To minimize this effect, a very small sample cell was made (3 mm dia. x 5 mm long) and the resonant coil was placed inside the cell providing a filling factor of 1.0.

Fig. 4 shows the effectiveness of signal averaging for the actual superconducting magnet. The original signal had a high noise level coming from the power supply. As can be seen, increasing the number of averages provides a clearer signal. The noise level is reduced from 1.5 V to 0.2 V providing an improvement by a factor of 8. According to the theory, the S/N ratio is improved by a factor of $\sqrt{N}$, where N is the number of scans that are averaged[2]. To get a better S/N ratio, the number should be increased, requiring a stable system for the longer time involved in date taking. There is some compromise for the number of scans per average, especially for the high current superconducting magnet that is excited by a noisy and unstable power supply. Averages of 64 scans are typically used, which take about 10 seconds.

Application to Superconducting Magnets

Two superconducting dipole magnets (E5-1 and E22-13) were measured with the above system[3] and the S/N ratio was found to be strongly dependent on the field quality. The probe was put in place where the field appeared to be most homogeneous. Magnets E5-1 (the precision model magnet) exhibited very good field qualities and a very clear proton signal (at 20 kG) was observed at the best point without averaging as shown in Fig. 5a. At higher fields, the field homogeneity is getting worse, as shown in Fig. 5b and 5c. At 44 kG, the ^{7}Li signal was observed only with signal averaging (Fig. 5c). The broadened line width suggests a large inhomogeneity. The twenty-two foot prototype magnet, E22-13, has poorer field qualities than magnet E5-1 and, for this reason, we could not even get a proton signal (below 21 kG) without signal averaging. We can estimate the field homogeneity over the sample from the line width. For example, the E22-13 has a homogeneity of 2×10^{-4} over the sample ($0.035\ cm^3$) at 20 kG. This value is reasonable compared with what is estimated from the harmonic coefficient.

The main measured item is the absolute dipole field value. Fig. 6 gives a transfer factor in units of G/A of E5-1 magnet as a function of the central field. It exhibits a hysteresis, which arises from the magnetization effect of superconductors, and also shows the saturation effect of steel core at high field.

It is essential to reduce the noise level as much as possible before signal averaging, especially for high field application. The 720 Hz noise coming from the power supply and the microphonic noise was partially reduced. The latter can be eliminated by mounting the probe on a stand, which is isolated mechanically from the magnet. The 720 Hz noise can be reduced by appropriate grounding. The absolute field inhomogeneity is another deteriorating factor. For example, even in a field with a homogeneity of $10^{-4}/cm^3$, the inhomogeneity amounts to 4 Gauss at 40 kG. In the actual dipole magnet, it is usually much worse than this value without correction. One possible way to compensate for this is to reduce the size of the sample; however, this also reduces the signal level. Even with an optimum sample size and signal averaging, it becomes difficult at high field over 40 kG to observe a ^{7}Lithium signal at field inhomogeneities above $10^{-3}/cm^3$. The use of a correction coil of quadrupole field on the probe may be useful to cancel part of field inhomogeneity, thus increasing signal.

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References

1 K. Borer: Private communications and to be published in Nuclear Instruments and Methods

2 M.P. Klein and G.W. Barton, Jr.: Rev. Sci. Instru., 34, 754 (1963)

3 R. Yamada, H. Ishimoto and M.E. Price: IEEE Trans. Mag-13, No. 1, 86 (1976), and this conference

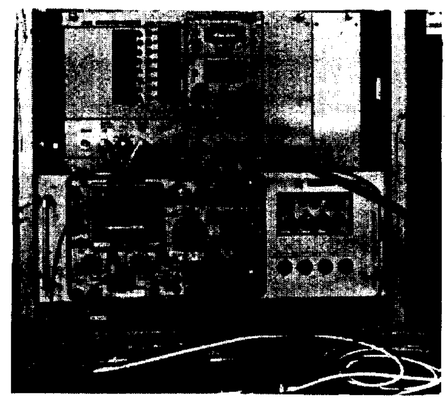


Fig. 1. NMR circuit and microprocessor signal averager with NMR preamplifier and probe in the foreground.

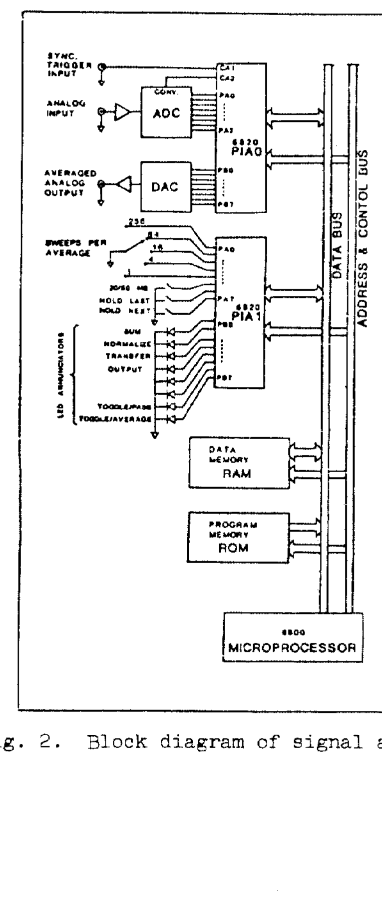


Fig. 2. Block diagram of signal averager

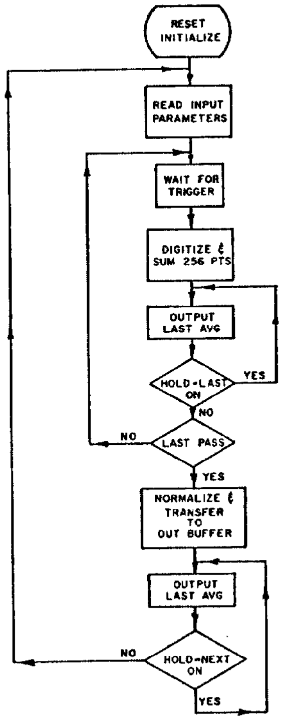
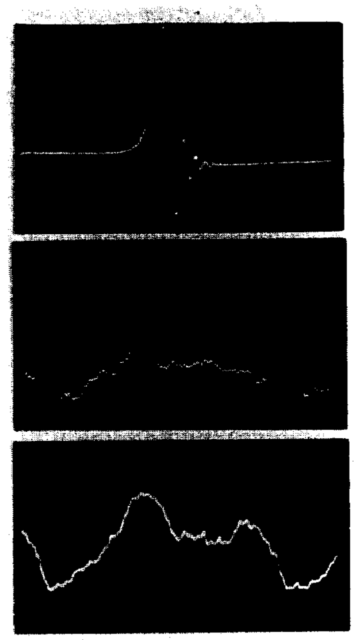


Fig. 3. Flow chart of signal averaging



(a) Proton

2,000A
85.661 MHz
= 20.12 kG

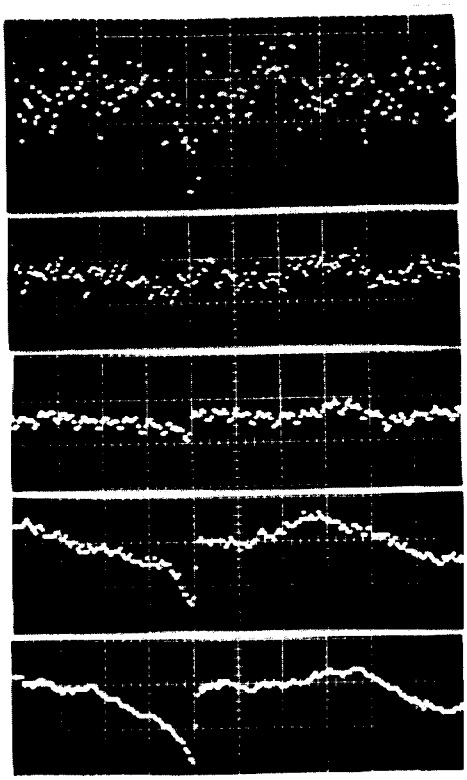
(b) ^{7}Li

3,000A
49.953 MHz
= 30.19 kG
after signal averaging

(c) ^{7}Li

4,400A
72.954 MHz
= 44.09 kG
after signal averaging

Fig. 5. NMR signal for E5-1 Magnet



(a) 1 V/div

(b) 2 V/div

(c) 2 V/div

(d) 1 V/div

(e) 1 V/div

Fig. 4. Proton signal at 20 kG for E22-13
x = 3.5 m sec/div
(a) no averaging (b) 4 scans (c) 16 scans
(d) 64 scans (e) 256 scans

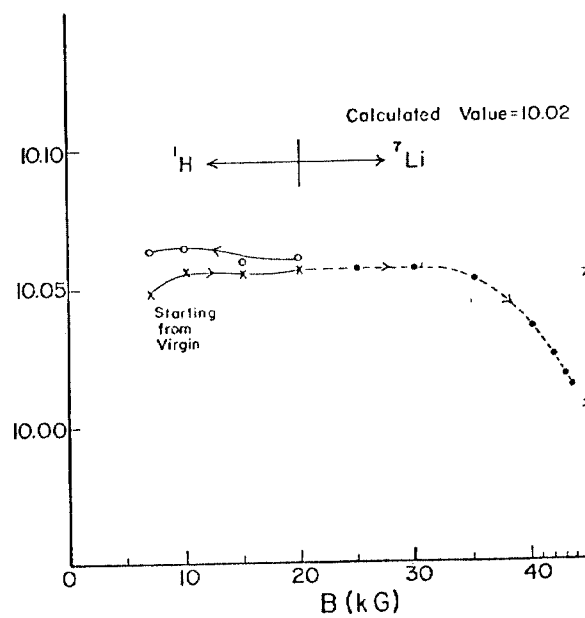


Fig. 6. Transfer factor versus central field for E5-1