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PRECISION NMR MEASUREMENT OF THE TRIUMF CYCLOTRON MAGNETIC FIELD

R. Burge, G. Dennison and D.A. Dohan
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Plans for separated turn operation and the need for improved stability in the present operation at TRIUMF require that drifts in the main magnet be reduced to <1 ppm. Stability of ±0.7 ppm for short periods (~10 min) were achieved with modifications to the present power supply. To improve the long term stability, a high resolution, high bandwidth, absolute method for magnetic field measurement is required. This paper describes an NMR system which uses a digital frequency synthesizer controlled by a CAMAC based microprocessor to determine the NMR resonant frequency. The system has been shown to be capable of measuring the TRIUMF magnet field with a resolution of 0.1 ppm, and a 10 Hz bandwidth. This system should allow the stabilization of the beam phase directly from the magnetic field measurement, a substantial improvement over a previous method where the required phase stability was obtained by modulating the RF frequency to compensate measured phase excursions of the extracted beam.

Introduction

In an ongoing program of improvements to the beam quality at TRIUMF, limits are being imposed on the allowed phase width of the beam, radial amplitudes, and variations in magnetic field, radio frequency and voltage. The eventual goal of separated turns at full extraction energy requires, in particular, that drifts in the main magnet field be reduced to less than ±0.7 ppm, for extended periods of time.

For the past two years, fluctuations in the main magnet field were measured using an NMR probe located near the center of one of the magnet hills. The NMR magnetometer, which was developed at CERN,[1] has a sensitivity of ±0.01G, or ±2 ppm of the hill field of 5.6 kG. Although this is not sensitive enough for separated turn requirements, it has been useful in studying low frequency magnet changes. Higher frequency fluctuations have been addressed by means of magnet power supply improvements. The beam itself has been used as an active feedback element but this has the inherent disadvantage in that a continuous extracted beam is required. The probe front end electronics has been troubled with component failure due to the high radiation fields. The present work was undertaken to overcome these limitations.

System Configurations

In a typical NMR system, the strength of the magnetic field is determined by a frequency counter which measures the NMR frequency of a water sample located in the field. To measure a 5 kG field to 7 significant figures with a bandwidth similar to the CERN unit, the frequency counter would have to operate at 10 times the frequency of the CERN unit.

Rather than continually measuring the NMR resonant frequency, the present system uses a programmable digital frequency synthesizer to provide a known RF source of sufficient precision. This establishes the necessary absolute accuracy required by the system. The synthesizer used in the present system, a Rockland model 5600, is programmable to 150 MHz with a resolution of 1 Hz and a settling time of 50 µsec. The Rockland synthesizer requires a 7-digit BCD input to program the frequency. This was provided by two 24-bit CAMAC output registers driven by a microprocessor. The microprocessor allows considerable freedom in the control loop and provides a mechanism by which the NMR system can control magnets via the CAMAC crate.

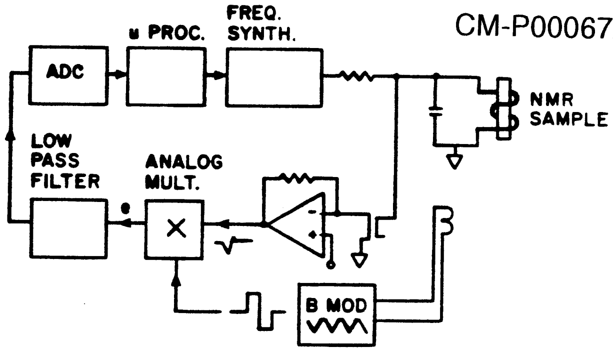

Fig. 1 Circuit Configuration

The NMR system behaves like a phase locked loop where the frequency synthesizer tracks the Larmor frequency of the proton resonance. The magnetic field seen by the water sample is swept by a current applied (at a repetion rate of 110 Hz) to a small coil near the sample. As this field is changed, the RF power absorbed by the sample passes through a maximum. When the loop is in lock, the absorption occurs when the B field modulation crosses zero.

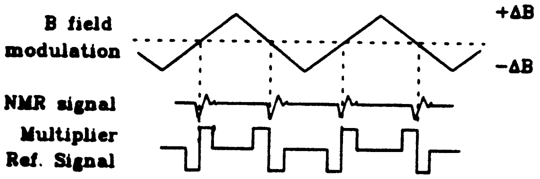

Fig. 2 NMR Waveforms

The offset between the synthesizer and the NMR frequency is transformed to an error voltage by the analog multiplier circuit. The entire NMR waveform is used to derive this error signal.

The NMR sweep (B field modulation) is a symmetrical sawtooth waveform. The average error voltage from the multiplier is zero when the synthesizer frequency causes the NMR signal to be symmetrical about the zero crossing of the field sweep. If there is a magnetic flux gradient across the NMR sample, then RF absorption occurs over a wider range of frequencies and hence the NMR signal appears broader. Integrating the entire waveform measures the total energy absorbed by the sample. This is less dependent on the signal form factor and has greater noise immunity than peak detection.

The window of the multiplier reference signal can be changed. In a search mode, it is opened up to the full square wave, whereas in a lock condition, it is closed down to improve the signal to noise ratio. Figure 3 shows oscilloscope displays of the Mixer output with the B field modulation waveform used as the horizontal input for the oscilloscope.

The disadvantage of the mixer circuit is that the error voltage requires a great deal of filtering to remove the sweep frequency component. The system uses a fourth order 10 Hz low pass filter. To achieve the

Fig. 3 Mixer Error Signals

Wide Window

Narrow Window

10 Hz bandwidth in the error signal, it is necessary to have a relatively high sweep frequency (110 Hz). Such an arrangement does provide good rejection of 60 Hz power line noise.

The high sweep rate also requires that the water sample be doped with a paramagnetic salt. This increases the ability to couple RF energy into the sample and decreases the dipole moment relaxation time. The NMR sample goes through resonance 220 times per second. The relaxation time must be smaller than half the sweep period. Doping the sample allows the energy to be absorbed and quickly decay so the resonance can be excited when the B field modulation crosses zero again. A 1 molar solution of $Ni(NO_3)_2$ is used.

The probe head contains the RF detector. The radiation fields near the main magnet destroy bipolar transistors in a few months. In the same environment, FET's have a lifetime of more than a year. A FET is used in a plate detector configuration to detect the RF absorption by the water sample. This detection method provides demodulation and signal gain in one active device. The NMR absoption signal can be directly cabled (up to 75 meters) to the primary amplifier with good noise immunity.

Control Loop

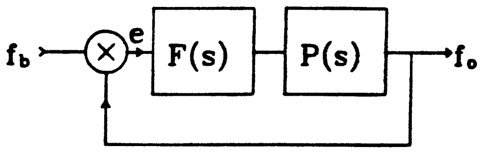

Fig. 4 NMR Loop Diagram

Figure 4 shows the loop diagram with the dominant loop elements, the low pass filter and the control program. f_b is the NMR frequency and f_o is the synthesizer frequency. F(s) is the low pass filter response, and P(s) is the control program response. P(s) is of the form $e^{-s\tau}\,[\frac{K_1}{s} + K_2]$ where τ is the control program delay in sampling the error voltage.

The loop response is given by

$$\frac{f_o}{f_b} = \frac{F(s)\,P(s)}{1 + F(s)\,P(s)}$$

The loop response is complicated by the 4th order low pass filter. This gives a 5th order polynomial in the denominator of the loop equation. Such a system is best optimized in a computer simulation.

The computer control of the feedback loop gives the system a great deal of flexibility for magnetic measurements. For small (a few ppm) changes in the magnetic field, the error signal is linear. The control loop can be modified to track long term ($t > 3$ sec.) and deliver the error voltage to a magnetic controller for correcting fluctuations faster than 3 seconds.

Results

The system was tested using a magnet with a 10 cm diameter pole face. Each pole was wound with an additional 5 turn test coil. One coil was excited by a signal generator to provide known field changes, whereas voltages induced in the second coil were integrated to measure the fluctuations in the magnetic field. These were compared with the measurements using the NMR system. A comparison of the two responses is shown in Figure 5.

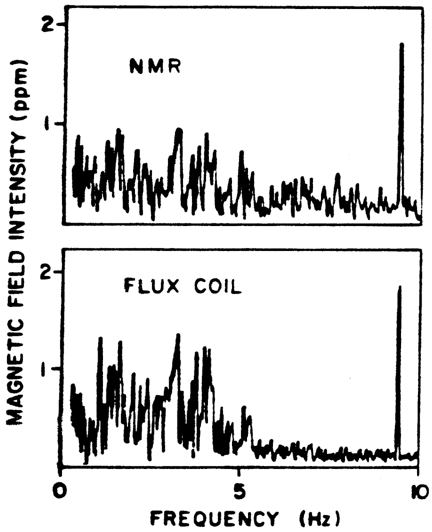

Fig. 5. Frequency Response Comparison of NMR and Coil Detection

To calibrate the system, a 10 Hz modulation of known magnitude was applied to the second test coil. The amplitude of the modulation corresponds to a field change of ±.0087 G, corresponding to a ±1.7 ppm fluctuation of the average B field. Figure 5 shows the 10 Hz bandwidth of the NMR detection ssystem, and shows that the system is capable of detecting fluctuations in the magnetic field of a few parts in 10^7.

Summary

A system for detecting magnetic fields has been described which has very stable D.C. characteristics as well as being capable of meauring very small changes (a few parts in 10 million) with a bandwidth exceeding 10 Hz. The detector system front end has been designed to minimize the number of active components required in the high radiation fields present in most cyclotrons.

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References

1. K. Borer and G. Fremont, The Nuclear Magnetic resonance Magnetometer Type 9298, N.I.M. 154 (1978) 61.