THE NUCLEAR MAGNETIC RESONANCE SYSTEM FOR THE
CERN MUON STORAGE RING

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ABSTRACT

The magnetic field strength in the muon storage ring has to be measured and stabilized to a precision of a few ppm. The ring consists of 40 contiguous magnet blocks and has a diameter of 14 m. Nuclear magnetic resonance (NMR) probes are used in each block for stabilizing and monitoring the field at the required precision.

The interchange accuracy of the NMR magnetometers and field stabilizers is ± 0.3 ppm. The short-term (1 hour) stability of the field is ± 0.2 ppm. The average field is reproducible to ± 1.5 ppm after switching on the magnet in a special way called "cycling"; after this the field rises some 5 ppm over three days, thereafter being stable within ± 1 ppm during weeks.

Various accuracy tests and absolute calibration of the NMR probes have been performed, and are discussed in a separate paper¹⁾ accompanying this description of the NMR system.

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1. INTRODUCTION

The new CERN Muon Storage Ring²⁾ (Fig. 1) began operation in June 1974. It was constructed for measuring the muon g-factor anomaly $a = \frac{1}{2} (g-2)$ to a precision of some 10 ppm³⁾. This can be achieved by storing muons of 3.1 GeV/c momentum in a precisely known homogeneous magnetic field, using an electrostatic quadrupole field for the necessary vertical focusing⁴⁾, and by measuring the precession frequency of the spin of the muons with respect to their momentum.

The (g-2) precession frequency is proportional to the magnetic field in the storage volume. In order to reach some 10 ppm as the combined statistical and systematic error of (g-2), this field has to be known, stable, and reproducible, to a precision of a very few ppm. The most practical method for achieving such a high precision is to use nuclear magnetic resonance (NMR)⁵⁾ for stabilizing and for measuring the field.

The muon storage ring has a diameter of 14 m at the centre of the aperture and consists of 40 contiguous C-shaped iron blocks, whose open sides face the centre of the ring. The 14 cm high and 38 cm wide gap contains the vacuum tank with the quadrupole electrodes, which leave an aperture of $8 \times 12 \text{ cm}^2$ free for storing muons. The whole ring is excited by four big concentric coils, which are connected in series. At the nominal field strength of 14.7 kG the power required is approximately 2 MW. The coil current is provided by a conventional rectifier power supply, and is stable at $\sim 5 \times 10^{-5}$.

The magnetic field in the storage region can only be mapped before and after the physics runs, because the vacuum tank has to be taken out of the magnet gap for this purpose. During the mounting and the dismounting of the vacuum tank the magnet has to be switched off. Therefore the long-term stability and the reproducibility of the magnetic field, when switching the magnet off and on again, have to be within a few ppm. Considering the size of the magnet, this requirement is very severe, although it applies rather to the average value of the field in the storage volume than to the local field at each point. That is why the field is stabilized individually in each of the 40 magnet blocks by NMR, i.e. each block has its own NMR probe and two compensating coils, wound around the yoke close to the magnet gap, for stabilizing the field.

Nuclear magnetic resonance is also used for mapping the field. Eight NMR probes are mounted on a measuring machine, which is driven around the ring by computer control. These probes are connected to eight fully automatic magnetometers, and measure simultaneously whilst the mapping machine is moving at a speed of up to 6 cm/sec. The NMR frequencies are measured and recorded by the computer, CAMAC electronics being used for this purpose. During a complete field map some 250,000 points are measured, which takes a time of about 10 h.

With the vacuum tank mounted in the magnet gap, the field can be monitored in 37 of the 40 magnet blocks. In these blocks an NMR probe can be driven into the vacuum tank, on a radial line in the medium plane, without breaking the vacuum. These 37 "plunging" probes are connected via eight multiplexers to the same eight automatic NMR magnetometers which are also used for mapping the field. The probe drive mechanism, the multiplexers, and the measurement of the NMR frequencies are computer controlled. Only 10 min are needed for measuring some 400 points with this "plunging" probe system. This is done once or twice a day during the physics runs.

It would have been very difficult and far too expensive to built up such a complex NMR system with commercial instruments. Therefore all the components of the system were designed and constructed at CERN. The design goal was not only accuracy and reliability at a modest price, but also to create a very easy-to-use NMR system. It is built mainly into NIM plug-ins. The most important modules are the NMR magnetometers and the NMR stabilizers. These dual-width NIM plug-ins need only very few electronic adjustments, at most once per year. All adjustments which depend on the field strength or homogeneity are automatically done by the units themselves.

No computer is needed for operating the NMR system, except for driving the mapping and the "plunging" probes into the wanted positions, and for measuring and recording the NMR frequencies produced by the magnetometers.

The relative accuracy of the NMR magnetometers and stabilizers is ± 0.3 ppm. That means that different magnetometers produce with the same probe in the same field within ± 0.3 ppm equal NMR frequencies. Similarly, different stabilizers connected to the same NMR probe fed by the same crystal-controlled RF oscillator set the field to within ± 0.3 ppm equal values. The absolute accuracy depends on the absolute calibration of the probes and is typically better than 1 ppm. This is treated in detail in a separate accompanying paper¹⁾.

2. REMARKS ON THE NMR TECHNIQUE USED

The theory and applications of NMR are widely covered in the literature⁵⁾. Let us just recall that a nucleus with magnetic moment μ can take, in the presence of a static magnetic field B_0 , $(2I + 1)$ distinct energy states, I being the spin quantum number. The separation of these states is $\Delta E = \mu B_0 / I$. Transitions between levels can be induced by applying an alternating magnetic field perpendicular to the static field, if its frequency equals the resonance frequency $f = \Delta E / h = \Gamma B_0$, with $\Gamma = \mu / hI$. For magnetic fields of the order of 10,000 G the NMR frequencies lie in the RF region. For protons Γ is known very precisely⁶⁾:

$\Gamma_{p,vacuum} = 4257.711(12) \text{ Hz/G}$ for protons in vacuum, and

$\Gamma_{p,H_2O} = 4257.602(12) \text{ Hz/G}$ for protons in a spherical sample of H_2O .

For the (g-2) measurement, however, the value of Γ_p is not very essential, since the magnetic field strength has to be known rather in terms of proton resonance frequency than in gauss³).

For detecting the proton magnetic resonance, a small water-filled coil is placed in the static field B_0 , with its axis perpendicular to B_0 . The magnetic moments of the protons in the water molecules point preferentially in the direction of B_0 , i.e. the lower energy magnetic states are more populated than the higher one. Therefore, if transitions are induced with an alternating field, those from lower to higher energy states are more frequent than vice versa. The protons absorb more energy from the alternating field than they supply to it, and the difference of the populations of the two energy states is reduced.

The thermal equilibrium populations are re-established due to spin-lattice interactions at a rate described by the so-called spin-lattice relaxation time T_1 . This is the reason why the protons continuously absorb energy from the alternating field, if the coil is driven at the proton resonance frequency, reducing thereby slightly the quality factor Q of the coil.

A practical way for detecting this effect is to tune a parallel LC resonant circuit with the water-filled coil as the inductor to the proton resonance frequency, and to apply to this tank circuit a stable sine wave of that frequency via a resistor. The resistor value should be chosen big as compared with the resonance impedance of the tank circuit, in order to avoid damping. If the proton resonance frequency is now modulated by superimposing a modulating magnetic field parallel to the static field B_0 , the reduction of the Q factor due to the proton resonance can be detected as a small amplitude variation of the RF voltage across the tank circuit.

This signal can be enhanced by adding a paramagnetic salt to the water. This reduces the relaxation time T_1 and therefore increases the steady-state energy absorption of the protons at resonance. Our NMR probes contain 0.1 molar $NiSO_4$ instead of pure water.

The modulating field B_{mod} is produced by a small, flat coil in the NMR probes. Its frequency is 30 Hz and its amplitude a few gauss. The magnetometer electronics detects and amplifies the resonance signals of the LC circuit and measures the current in the modulating coil at the instant when the resonance occurs. A voltage-controlled oscillator produces the RF voltage. Its frequency is controlled by a high gain feedback loop, such that the resonance occurs at the instant when B_{mod} crosses zero. Therefore this frequency equals the proton resonance frequency of B_0 .

and follows automatically any changes in B_0 . The LC circuit is automatically tuned to the applied frequency by means of a varicap diode.

The NMR field stabilizers work very similarly, but the voltage-controlled oscillator is replaced by a crystal-controlled one, and a high gain feedback loop adjusts the current in the compensating coils of the corresponding magnet block, such that the proton resonance occurs at the zero crossing of the modulation.

In concluding these general remarks, it should be mentioned that the field modulation in the NMR probes sweeps far too fast through the resonance to obtain adiabatic conditions. Therefore, the observed signals have neither the form nor the width of the real proton resonance curve (i.e. the form found for very slow crossing of the resonance). The width is about 18 ppm, which is several times the natural line width and transient effects, like for example "wiggles", appear (Fig. 2). However, this fast modulation is convenient for practical reasons, and an accuracy better than 1 ppm is nevertheless achievable, using a symmetry criterion. This subject is discussed in more detail in Section 4.

3. THE PRECAUTIONS TAKEN TO ACHIEVE THE REQUIRED REPRODUCIBILITY OF THE MAGNETIC FIELD

As already mentioned, the muon storage ring is composed of 40 contiguous magnet blocks, which are all stabilized individually by means of NMR. This is necessary but not sufficient to achieve the required field reproducibility of a few ppm. The average field in the ring may well change some 50 ppm if the magnet is switched off and on again without special precautions. This happens in spite of the fact that the field strength, at the 40 points where the stabilization NMR probes are located, is set always within better than ± 1 ppm to the same values given by the eight crystal frequencies used.

It is likely that eddy currents in the solid-iron yoke produce hysteresis effects, which can change the field map by as much as 10^{-4} . A well-known method for avoiding this is to saturate the magnet completely and afterwards to lower the field very slowly to the wanted value. This method could not be applied for power reasons. But another method, called "cycling", turned out to be very successful.

Figure 3 shows the time diagram of this special turning-on procedure. It starts with three and a half fast up and down cycles, with a rate of change of the current of 50 A/sec and with the current maxima at 4600 A, which is 10% higher than the current I_0 for the nominal field value. After this the current is run down slowly, at about 1 A/sec, to 5% below I_0 , and then up again, at the same rate, but only to 4% above I_0 , then down again to 3% below I_0 , and so on. Every time when the field equals the nominal value, the NMR signal appears in the stabilization probes. This flag is used as absolute reference for this second, slow part of the cycling, which

ends after three slow oscillations with decreasing amplitude. The NMR stabilization is switched on automatically at the end of the cycling.

It is also necessary to keep the cooling water and the room temperature constant to $\pm 1^\circ\text{C}$, in order to ensure the field stability at the ppm level.

4. DESCRIPTION OF THE AUTOMATIC NMR MAGNETOMETER

An over-all view is given in this section; some circuit details will be discussed later in Sections 5 and 7. Figure 4 shows a block diagram of the NMR magnetometer, which consists of a main unit (NIM plug-in) and a small probe amplifier box with the measuring head at a distance of some 30 cm (Fig. 5). The measuring head contains a flat coil for modulating the field in a small plastic bulb, which is shrunk around a cylindrical RF coil of 2 mm diameter and 4 mm length and which contains a 0.1 molar solution of NiSO_4 . The applied field modulation is a symmetric 30 Hz triangular wave form with a peak-to-peak amplitude of 8 G.

The RF coil, a tuning diode, and the coaxial cable from the probe box to the measuring head, form a parallel LC resonant circuit. This resonant circuit is weakly coupled by means of a $5.6\text{ k}\Omega$ resistor to the output of an RF amplifier with stabilized output signal amplitude. It is automatically tuned to the applied frequency of about 63 MHz. If this frequency is close enough to the proton resonance frequency corresponding to the main magnetic field B_0 , an absorption signal (i.e. amplitude variation) appears in the LC circuit every time the resonance is crossed due to the field modulation. This signal is amplified in the probe box and sent to the main unit.

A sample-and-hold circuit produces an error voltage which is proportional to the modulating field at the instant when the proton resonance occurs. With this "error voltage" the frequency of the RF oscillator in the main unit is regulated in such a way that the proton resonance occurs exactly at the zero crossing of the modulation. This frequency f , which is measured with an external counter, is therefore equal to the proton resonance frequency of the field B_0 seen by the protons in the water sample without modulation. It follows automatically all changes of B_0 within the oscillator range of about 62 to 64 MHz.

In a homogeneous field of 14.7 kG we obtain a signal-to-noise ratio of typically 50 to 100. As already mentioned, the line width is about 18 ppm, which is much more than the natural line width of our NiSO_4 solution. This is due to the fast crossing through the resonance, determined by the frequency and amplitude used for the field modulation B_{mod} , which results in a line width of

$$\Delta f \sim \frac{1}{\Delta t} \sim \sqrt{\frac{\Gamma_p}{P} \frac{dB_{\text{mod}}}{dt}} \sim 1400 \text{ Hz} .$$

The kind of field modulation used is justified in the following way: With a modulation of a few gauss amplitude it is easy to find the NMR signal and to keep the magnetometer locked to the field. Considering the tracking speed of the RF-oscillator needed for mapping the field and the above line-width argument, a modulation frequency of 30 Hz was found to be a reasonable compromise between line width and response time. In spite of the increased line width of the NMR signal, an accuracy well below 1 ppm can still be reached, provided that the LC resonant circuit in the probe is well tuned to the applied frequency and that the field modulation is symmetric with respect to zero, i.e. $B_{\text{mod}}(t + T) = -B_{\text{mod}}(t)$, $2T$ being the period of the modulation. With both conditions fulfilled the NMR signals become identical in form and size and equally spaced in time if the resonance occurs at the zero crossing of the modulation (Fig. 2).

It is therefore not necessary to know *a priori* at which point of the 18 ppm wide signal the applied frequency is equal to the proton resonance frequency. The criterion is simply that the time difference between any point of the NMR signal and the close-by zero crossing point of the modulation is equal for upward as well as for downward going modulating field. Then the applied frequency is equal to the proton resonance frequency of the field B_0 with $B_{\text{mod}} = 0$, and this is the criterion upon which the frequency control loop works.

If the LC resonant circuit is mistuned, a dispersion signal is mixed with the absorption signal, and the NMR signals at upward zero crossing of the modulation look different from those at downward zero crossing. With the probe 1% mistuned (i.e. LC resonance frequency 1% different from applied frequency) the resulting error in the proton resonance frequency would be about 3 ppm. But the automatic tuning circuit guarantees that the mistuning is less than 10^{-4} over the whole frequency range, making this kind of error negligible.

The symmetry of the modulation is also important for getting identical NMR signals for upward and downward zero crossing. Therefore an internally generated triangular wave is used rather than line modulation. This wave form can be easily generated very symmetrically and crosses through zero more slowly than a sinusoidal wave of the same frequency and amplitude, which reduces the line width.

The automatic tuning of the probe and the good symmetry of the field modulation are the basis for the high accuracy of the magnetometer. To achieve a short response time of the frequency control loop, the sample-and-hold circuit mentioned above is used to produce an "error voltage", which indicates after each NMR pulse how much the resonance was away from zero modulation, the sensitivity being 1 V/G. This error voltage is integrated and sent thereafter to the frequency control input of the RF oscillator. By choosing the gain and the integration time constant appropriately the error can be corrected entirely within the time between two consecutive NMR signals. Therefore, for this optimum loop gain setting, the time lag

of the frequency tracking is equal to the spacing of the NMR signals, which is roughly 17 msec. The loop gain at d.c. is of the order of 10^6 .

The NMR signals get smaller and wider in inhomogeneous fields. At a gradient of 5 G/cm, which is about the operation limit of the magnetometer, the amplitude reduction is roughly a factor of 10. Therefore the trigger level and the timing of the sample-and-hold circuit are adjusted automatically in the main unit in order to maintain optimum performance also if the signal size and form vary, as for example during the field mapping. The trigger level is set automatically to about half the signal amplitude, the latter being measured with a special peak detector circuit, which is insensitive to possible occasional large single parasitic signals.

The trigger point may be early or late with respect to the proper proton resonance. In order to correct this, both the strobe pulse as well as the triangular wave voltage, proportional to the modulating field, are delayed appropriately before being fed to the sample-and-hold circuit which produces the error voltage. Wrong timing does not change the mean value of the error voltage, but produces a 30 Hz rectangular signal superimposed on it and synchronous to the modulating field (see Fig. 6). It is therefore rather the speed than the accuracy of the field measurement which would deteriorate. However, the delay of the strobe pulse is adjusted automatically by the magnetometer, such that the mentioned 30 Hz component of the error voltage disappears.

If no NMR signals are detected, the magnetometer switches itself into a search mode. In this mode the RF oscillator sweeps at about 1 MHz per second up and down through its whole frequency range. As soon as an NMR signal appears, the magnetometer switches itself into the "lock" mode, where the frequency tracking loop is closed.

5. THE PROBES

5.1 Circuit description

The complete circuit diagram of a probe is given in Fig. 7. The NMR signals of typically ≤ 1 mV are detected in the conventional way with two (Schottky) diodes, and thereafter amplified 3000 times. Since the gain of the NMR signal amplifier is one at d.c., the voltage level at this output indicates the RF amplitude at the LC resonant circuit, typically a few hundred millivolts.

Special attention has been paid to reducing any amplitude modulation and noise of the incoming RF signal. This is of great importance for a good signal-to-noise ratio, especially if several probes are fed through long cables and operated simultaneously at slightly different frequencies (risk of "beating"!). With a typical RF input of 500 mV peak-to-peak the amplifier CA 3028 operates in a switching mode

rather than linearly and is hardly sensitive to the input amplitude. Moreover, the output amplitude of the RF amplifier is measured with a second diode detector circuit and stabilized with a gain control loop. Both together result in a smoothing factor of 50 to 100.

5.2 The automatic probe tuning

Although the circuits for generating the varicap voltage are located in the main unit for space reasons, their operation is discussed in this section, because the automatic tuning is a very essential feature of the probe. The circuit diagram is given in Fig. 8. A 10 kHz square wave signal of 20 mV amplitude is superimposed on the varicap voltage. The capacitance of the LC resonant circuit is therefore very weakly modulated with this signal ($\Delta C/C \approx 10^{-4}$). This results in a 10 kHz amplitude modulation, if the resonant circuit is slightly mistuned, being in phase or 180° dephased with respect to the injected square wave, depending whether the capacitance is too small or too big.

The amplitude modulation is detected and amplified by a factor of 3000 together with the NMR signal. The superposition of both is fed to the x-input of an analogue multiplier MC 1494L, where the NMR part is reduced by RC differentiation and diode clipping, the latter being necessary in order to avoid spurious signals when there are big and slowly decaying wiggles. The y-input of the multiplier is connected to the 10 kHz square wave generator, which produces a bipolar output signal of ± 10 V. The same signal is used after attenuation by a factor of 1000, for modulating the varicap.

In this way a positive or negative current is produced at the multiplier output, whenever the resonant circuit is mistuned. This current is fed to an integrator which changes the varicap bias voltage until the multiplier output current falls to zero, i.e. the 10 kHz signal at the x-input disappears. The time constant has been chosen such that the automatic tuning easily follows the frequency variation of about 1 MHz/sec in the search mode. The precision of the tuning for slowly varying frequency is better than 10^{-4} and is not limited by the loop gain ($\sim 10^7$ at d.c., one at ~ 300 Hz), but rather by second-order effects like, for example, the modulation of the capacitance by the RF voltage.

5.3 The measuring heads

As can be seen from Fig. 9, the physical dimensions are rather small. The flat field modulating coil is wound on a support made of loaded araldite, with outer dimensions of $3 \times 8 \times 14 \text{ mm}^3$ and with a rectangular hole of $3 \times 3 \times 10 \text{ mm}^3$ for the plastic bulb with the water sample. The monitoring probes fit into a tube of 10 mm inner diameter. In the stabilization probes the axis of the water sample is parallel to and at a distance of only 4 mm from the front edge of the measuring head. This allows the reference points for the field stabilization to be very close

to the vacuum tank, which is important since the field becomes inhomogeneous rapidly, and less representative of the field in the storage volume at increasing distance from the vacuum tank.

The polyethylene tube, which contains the water sample, is shrunk by heating around the RF coil (9 turns, 2 mm diameter, 4 mm length) and tightened at both ends with droplets of the same, melted material. Putting the RF coil inside the tube results in an optimum filling factor, but limits the lifetime of these samples to typically one year, because the water disappears slowly, probably through tiny leaks at the wire feedthroughs.

The modulating field in the water sample is not very homogeneous. This does not harm the accuracy, since the resonance occurs when the modulating field goes through zero, but it has the welcome effect of damping the wiggles.

6. DESCRIPTION OF THE FIELD STABILIZATION

6.1 Discussion of the block diagram and the Bode plots

Figure 10 shows the block diagram of the NMR field stabilization of one magnet block. It is built up from the same circuits as the magnetometers, but the RF signal for the probe is produced by an external crystal-controlled oscillator and the NMR error voltage is used for controlling the current through two compensating coils wound around the yoke close to each pole and connected in series. To increase the bandwidth of the stabilization, a pick-up coil (100 turns of 0.22 m² area) is placed on the pole face of each block in the space between the shims. The induced voltage is integrated and combined with the NMR error voltage in such a way that the pick-up coil dominates the NMR probe at frequencies above 1 Hz and vice versa below 1 Hz.

Figure 11 shows four Bode plots, i.e. the frequency response curves of the main four paths in the stabilization loop. Curve 1 represents the path from the NMR probe to the input of the power amplifier point A. The 6 dB per octave slope is due to the time constant of 15 msec in the feedback of the summing amplifier, the NMR error voltage frequency response being constant (1 V/G) from d.c. to about 15 Hz. Curve 2 shows the contribution of the pick-up coil at the same point A. This curve is flat for $f > f_1 \sim 0.7$ Hz, since the integration and the differentiation at the summing amplifier cancel each other due to equal time constants. The gains are chosen such that the curves 1 and 2 cross each other at 1 Hz. Curve 3 shows the field as measured with the pick-up coil, when a sine-wave voltage with constant amplitude and varying frequency is applied to the compensating coils. The voltage gain of the power amplifier is 100 and constant from d.c. to about 10 kHz.

Curve 4 represents the loop gain and is the sum of curves 1 and 2 multiplied by curve 3 and by the power amplifier voltage gain of 100. The loop gain is greater than 10^6 at d.c. and falls off with increasing frequency at roughly 6 dB per octave, reaching unity at about 800 Hz. However, at frequencies above 10 Hz, it is mainly the flux in the pick-up coil which is stabilized and less the local field in the magnet gap, the latter being influenced rather randomly by the compensating coils at such frequencies, due to eddy currents in the solid iron yoke.

A (partly) active filter has been connected between the 2 MW power supply and the magnet. It reduces the rectifier ripple voltage and other possible fast fluctuations of the voltage applied to the magnet coils to such a low level that the short term (0.2 sec) peak-to-peak variations of the field, with the NMR and pick-up coil stabilization switched off, are less than 1 ppm. Therefore, the frequency response of the combined NMR and pick-up coil stabilization is quite sufficient. Even a much slower version of pure NMR field stabilization without pick-up coil gave almost the same good results as the combined system.

6.2 The search mode

When no NMR signals appear in a stabilizer, it switches itself into a search mode. In this mode the current in the compensating coils is zero and the field modulation in the probe is increased to ± 15 G which covers well the range of the compensating coils of about ± 10 G. Therefore the NMR signals reappear; if the main field is not out of the stabilizer range, the stabilization loop is closed again and, after 1 sec delay, the modulation is switched back to ± 4 G.

6.3 Feedback to the magnet power supply

The output voltage range of the power amplifiers is ± 15 V, which is equivalent to ± 10 G at d.c. But in order to avoid changes of the field shape, the average of the 40 compensating coil currents is kept close to zero in the following way: the current in the main coils is automatically readjusted when the mean value of the 40 compensating coil voltages exceeds ± 1 V.

7. CIRCUIT DETAILS

Figure 12 shows the diagram of the error voltage generating circuit, including the automatic threshold and timing controls. The integrated sample-and-hold amplifier and the MOS-FET switch in the automatic delay circuit were not used in the early version of the NMR circuit of the (g-2) experiment, but have been introduced very successfully in later versions.

The trigger threshold of comparator C1 is 0.6 times the voltage at point A, which is produced by the circuit around A1 in a charge pumping mode, and which

is 15% less than the NMR signal amplitude. This kind of amplitude detection has the advantage of being hardly sensitive to occasional large single parasitic signals, since the voltage at point A can change at most 0.2 V per input pulse of any size.

The modulating current I_{mod} is sampled during the 30 μsec pulses produced by the one-shot 2 (shown in Fig. 12). The pulse width is not critical, but has to be long enough to allow the sample-and-hold amplifier to settle. The delay relative to the instant when the NMR signal crosses the threshold at C1 is determined by the voltage at the output of the integrator A4. This voltage is regulated so that no 30 Hz component appears at the error voltage output. If there is a signal in phase or 180° dephased relative to the modulation, it is amplified by A2 and integrated by A4 during only the positive half waves of the modulation, the MOS-FET switch being controlled by A3. This results in a decrease or increase, respectively, of the output voltage of A4 and therefore in a decrease or increase, respectively, of the delay, until the 30 Hz component disappears.

The three diodes and the Zener diode limit the output voltage of A4 to values safely above the baseline and below the top of the pulse at the inverting input of C2. The range of the automatic delay is about 0 to 2 msec, which is, considering the fixed delay of 0.5 msec at the sample-and-hold input, equivalent to -0.5 msec to +1.5 msec. This is quite sufficient for all practical operating conditions of the NMR magnetometers and stabilizers.

Figure 13 shows the circuit diagram of the voltage-controlled oscillator in the magnetometer and the circuit which produces the frequency control voltage in the tracking mode. The Colpitts-type oscillator is enclosed in a metal box for interference and stability reasons. An ECL gate with well-filtered supply voltage produces the RF signal for the NMR probe. This results in a low noise level, and the square wave rather than sinusoidal shape of the RF signal is not harmful.

The frequency control is linearized with a resistor-diode network, in order to maintain the loop gain constant over the whole frequency range.

8. THE MULTIPLEXERS FOR THE MONITORING PROBES

The 37 "monitoring" probes are connected to eight magnetometers by means of eight 5-channel multiplexers. Each multiplexer supplies its five NMR probes simultaneously with the regenerated RF signal of its magnetometer, again ECL gates being used for this purpose. It contains also five automatic tuning circuits, in order to keep all probes tuned and ready for locking to the field when selected by the computer. Only the field modulation and the NMR signals are switched by means of relays to the selected channel.

9. AUXILIARY ELECTRONICS

By adding some auxiliary control and test electronics the NMR stabilization system was made completely autonomous. It consists of a magnet control unit, a cycling box, eight stabilizer control units, and a stabilizer test unit.

The magnet control unit controls the main coil current setting, so as to minimize the average of the compensating coil currents when the NMR stabilization is on. It is also used for switching on the magnet with "cycling", the timing of which is controlled by the cycling box. The communication with the stabilizers is done via the stabilizer control units, where the information of all five stabilizers on the error voltage, the compensating coil current, and eventual lost NMR signal, is summarized.

The control units also transmit an inhibit signal to all stabilizers for vetoing any wrong "NMR signals" due to pick-up from the inflector and quadrupole pulsing. The NMR signals, error- and compensating-coil voltages of all stabilizers are available at the stabilizer test unit by push-button selection, and an alarm is produced if any stabilizer goes wrong.

Also for the field measurements with the 37 monitoring probes some test and control electronics, linking the computer with the magnetometers and the multiplexers, is needed. Switching the multiplexers from one probe to the next may cause loss of the NMR signal. The frequency measurement is only initialized one second after all magnetometers detect an NMR signal, and any magnetometer faults during the frequency measurement time are transmitted to the computer.

10. FURTHER DEVELOPMENTS

The development of a wide field range version of the described magnetometer is nearly completed. Fields between 1.3 and 21 kG can be measured with four proton probes, and two deuteron probes can be used for fields between 20 and 65 kG.

Essentially the same circuits as in the (g-2) magnetometers are used, but the frequency range of the oscillator has been increased to between 30 and 90 MHz, and three flip-flops have been added to divide the oscillator frequency for the three lower field ranges and for the two highest field ranges with the deuteron probes. Also the range of the automatic tuning of the probes has been increased accordingly. The search and frequency tracking range is a few per cent and the coarse adjustment of the frequency has to be done manually.

An improved layout of the printed circuit and of the mechanics leaves enough space in the double-width NIM module for a frequency counter, indicating the field strength in gauss with a resolution of a hundredth of a gauss.

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Figure captions

- Fig. 1 : The muon storage ring at CERN.
- Fig. 2 : NMR signal and modulation field: chopped $y(t)$ display. The scope is triggered with the NMR pulses, alternatively at upward and downward going modulation field.
- a) The "alignment" of the NMR pulses in the frequency tracking mode.
 - b) A magnified display of the central part of (a).
 - c) The "misalignment" resulting from a 1 ppm frequency error [same scale as (b)].
- Fig. 3 : Time diagram of the "cycling".
- Fig. 4 : Block diagram of the NMR magnetometer.
- Fig. 5 : NMR magnetometer with probe amplifier box and measuring head.
- Fig. 6 : A 30 Hz square wave component in the error voltage indicates wrong timing of the sample-and-hold circuit. In the example shown, the sampling pulses are assumed to be early in respect to the nuclear resonance.
- Fig. 7 : Circuit diagram of the NMR probe.
- Fig. 8 : The circuits for the automatic tuning of the probe.
- Fig. 9 : The measuring heads of the stabilization and field mapping probes (up), and of the monitoring probes (down).
- Fig. 10 : Block diagram of the NMR field stabilization.
- Fig. 11 : Some Bode plots of the field stabilization.
- Fig. 12 : The circuits for generating the error voltage, including the automatic threshold and timing controls.
- Fig. 13 : The voltage-controlled oscillator and the associated circuits for the frequency tracking.

Fig. 1

a)

1 V/div.

Time scale: ~ 4 msec/div.

2 G/div.

b)

1 V/div.

Time scale: ~ 0.4 msec/div.

2 G/div.

c)

1 V/div.

Time scale: ~ 0.4 msec/div.

2 G/div.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

- ① MODULATING FIELD
- ② ERROR VOLTAGE
- RESONANCE POINTS
- + SAMPLING POINTS

Fig. 6

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13