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AN MC68000 MICROPROCESSOR CAMAC SYSTEM

FOR NMR MEASUREMENT OF POLARIZATION

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ABSTRACT

An MC68000 microprocessor CAMAC system has been designed for accurate nuclear magnetic resonance signal measurements. The system works as a fast signal averager and allows optimization of noise suppression. The processor software is controlled by a minicomputer which sees the MC68000 as a normal CAMAC module. The processor front-bus can be extended to several interface modules. Several of these processor systems can be installed in a CAMAC crate for parallel processing.

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1. INTRODUCTION

This paper describes a nuclear magnetic resonance (NMR) polarization measurement system, which uses an MC68000 microprocessor for signal averaging and commanding of a radiofrequency (RF) synthesizer.

The aim of the work has been to improve the speed and accuracy of the polarization measurement in polarized targets. This is needed for fast polarization reversal with on-line computer optimization of the microwave frequency and power. The fast polarization reversal is required in high-energy inclusive polarization asymmetry measurements [1-3], where normalization of the luminosity is not possible using the background technique of elastic-scattering experiments.

It has been shown rigorously [4] that the polarization $P_I = \langle I_z \rangle / I$ of spins I can be determined from the imaginary (absorption) part $\chi''(\omega)$ of the RF susceptibility

$$\chi(\omega) = \chi'(\omega) + i\chi''(\omega) \quad (1)$$

by integration over the frequency domain

$$P_I \propto \int_0^\infty \chi''(\omega) d\omega. \quad (2)$$

This is valid when the RF excitation for the susceptibility measurement causes negligible saturation, i.e. change in polarization. The RF absorption signal can be conveniently measured in polarized targets with a series resonant Q-meter [5], the output of which responds linearly to $\chi''(\omega)$ when $\chi(\omega)$ causes a relatively small ($< 10\%$) impedance change in the resonant circuit.

The calibration of the Q-meter is usually done by measuring the surface area of the absorption signal with thermal equilibrium (TE) polarization. The TE can be reached at 0.7-1.0 K temperature in less than one hour. The TE polarization of spins I at temperature T is

$$P_I = B_I(\hbar\omega_I/k_B T) \quad (3)$$

where B_I is the Brillouin function for spin I ; at 1 K temperature and 2.5 T field this gives a proton polarization of $P_p = 0.25\%$. If the circuit is made to respond

with $\leq 10\%$ impedance change for complete spin polarization, the TE signal would then cause 2.5×10^{-4} impedance change. This can be measured easily by the use of signal averaging, even with non-saturating RF field.

Under the above TE conditions a deuterated material would give a signal several hundred times smaller, because of the deuteron magnetic moment eight times smaller than that of the proton, and the quadrupole-broadened NMR line. So far the quantitative calibration of the deuteron signal has not been possible with the TE technique, owing to circuit instabilities during long averaging periods. This may be overcome by our new fast averaging technique.

The frequency agility of the microprocessor-commanded RF sweeper allows easy switching to more exotic spin species, such as ^{13}C , ^{14}N , and ^{15}N . The measurement of their NMR signals is often necessary for the understanding of the basic mechanisms by which dynamic nuclear polarization (DNP) works. Our new set-up should be particularly valuable in these measurements. The presently used NMR set-ups [6,7] at CERN have hard-wired CAMAC interfaces, which are controlled by a minicomputer and external clocks. A system based on a direct synthesizer and an LSI-11 microcomputer has been used at Rice University [8]. At TRIUMF a similar system has been built using two 8-bit microprocessors [9]. The advantage of our system is that it allows continuous averaging of several signals, with dead time only during a command or a data transfer (less than 5 ms for our normal averaged signal).

2. THE NMR SET-UP

Our Q-meter NMR circuit, shown in fig. 1, consists of an RF synthesizer*), a series resonant circuit with a resonant cable in between the tuning capacitor and the NMR coil, RF amplifiers, and a phase-sensitive detector, followed by post-detection amplifiers and filters [10]. The phase-sensitive detector selects the real part of the signal, reducing the depth of the Q-curve so much that its compensation before digitization is not necessary in the case of proton signals.

The NMR set-up is shown schematically in fig. 2. It operates as follows: the MC68000 processor commands the sweep of the frequency synthesizer step-wise.

*) Rockland Model 5600

At each frequency step, after a programmable delay for letting all circuitry settle, the processor commands the analog-to-digital converter (ADC) to convert the signal into digital value, which is added and stored in a corresponding memory location. After a programmable number of sweeps, the processor stops and sends a look at me (LAM) signal to the HP minicomputer, which can command reading the accumulated signal in a block transfer.

The averaged signal is then treated in the minicomputer for base-line subtraction and calculation of the moments of the resonant line up to the fourth moment. These are further treated to get the polarization, line width, line shape, and peak position and height. The HP program (written in FORTRAN or BAMBI) can furthermore fit the wings of the line for improved accuracy of the moments and therefore of the above parameters. During the analysis of the signal, the MC68000 is accumulating data on the next one.

An oscilloscope is used for tuning the RF circuits, during which time the processor is set to sweep the frequency continuously without LAM signals to the minicomputer. The horizontal sweep of the oscilloscope can be taken from a digital-to-analog converter (DAC), which is programmed to increment and decrement synchronously with the frequency steps. Alternatively, the scope can be triggered by a signal from the control logic of the NMR interface, so that also the time-base mode can be used.

3. THE MC68000 CAMAC MODULE

The MC68000 CAMAC module (68KCM) is made on a single CAMAC circuit board, using wire-wrap technique, and is three slots wide. The width can be reduced to two or maybe even one unit, by using a less space-consuming wiring technique.

On the circuit board is:

- i) 6 kbyte Random Access Memory (RAM)
- ii) 12 kbyte Erasable Programmable Read Only Memory (EPROM)
- iii) a CAMAC interface
- iv) 2 serial interfaces

plus the usual logic and a 60-pin 3M front-bus connector; see fig. 3. The front-bus connects the processor module and the NMR interface together, which provides optimum control for the MC68000 of the interface. Also more than one interface can be connected to it at the same time. The front-bus is a full processor bus with all address, data, and control lines, except that the address lines are reduced from 24 to 18, and only one level of interrupts can be given. This is done because flat-cable connectors of more than 60 pins are not easily available, and take a lot of space. This bus is adapted for our specific use; however, a standard connector and well-defined pin layout would be desirable to make the front-bus more useful for a wider variety of applications. The RAM and EPROM capacity could easily be doubled using the denser memory circuits available today.

The CAMAC interface is a bidirectional 16-bit latch as dataway, allowing information transfer from MC68000 to HP and reverse, and an 8-bit directional latch for all function lines and 3 subaddress lines, from HP to MC68000 only. The 68KCM behaves like a normal module in the crate and is not a controller.

The MC68000 software is written in assembler language, using a cross-assembler on CERN's IBM. The terminal and host connection as drawn in fig. 2 are only for software development. For normal use the program will be stored in EPROM and start from a power-on/reset. The program has a monitor which recognizes CAMAC functions at the slot address of the processor, and makes the processor perform the desired function. As it can perform many more functions than a normal (only hardware) CAMAC module, the standard CAMAC calls such as Read register, Write register, Enable, etc., are not sufficient. To overcome this without changing the existing function definition, the data are taken as information on what to do at the first Write (F16) instruction. In this way 65536 new jobs can be commanded with a single CAMAC (16-bit) transfer. To give an idea, some new functions used for the processor are: Initialize data taking, Start data taking, Send accumulated data. Other functions, followed by a second data word can, for example, change the start frequency, change the frequency step, change the number of steps, etc. To have a proper data exchange with the processor a software handshake has been made in the

following way: After each command the processor will generate a LAM signal and send a status word across at the next Read instruction. The status word is normally 0; any other value means an error message, which can be defined, for example, as 1 = wrong sequence of commands, 2 = attempt to load a parameter (like start frequency) which is too big, etc.

4. THE NMR INTERFACE MODULE

The NMR interface module is also a single CAMAC circuit board, 3 slots wide, made with wire-wrap technique. This interface does not have an interface to CAMAC and is fully controlled by the 68KCM, for fast data acquisition. The use of the different blocks drawn in fig. 4 is described briefly below.

- i) A Sample and Hold amplifier (S/H). The S/H holds the signal of the Q-meter to keep the signal stable during the conversion of the ADC, isolating any transient in the Q-meter output. This allows a simultaneous frequency change of the synthesizer, during ADC conversion. The S/H settles to 0.01% in 15 μ s, and droops 50 μ V/ms.
- ii) A 14-bit ADC. The ADC converts the analog Q-meter signal so that digital accumulation can be done by the processor. The conversion time is 12 μ s.
- iii) Two 12-bit DACs. One DAC is used to output a ramp synchronous with the sweep, used as horizontal axis for the scope. The other DAC is foreseen for supplying an offset to the analog signal to use the maximum range of the ADC, which is from -5 to +5V, independent of the signal polarity.
- iv) Latches for frequency setting of the synthesizer (32 bits, BCD). These latches keep the desired frequency as input to the synthesizer. This frequency is usually changed by the processor with two 16-bit-word Write instructions (long word operation). This does not cause a double transient in the output, because the synthesizer does not latch-in this frequency until the processor has given a 'Store' command.

- v) An 8-bit buffer/latch for MC68000 device control and trigger inputs and outputs. The 8-bit buffer/latch is the key of the control for the MC68000. By setting or resetting the bits it can command the S/H to sample or hold, the ADC to convert, the synthesizer to store the frequency, and give a trigger and/or intensity modulation output to the scope. By reading other bits in the latch the processor can see when the ADC has finished the conversion or when a synchronization pulse has been given from an external device (like the SPS trigger for example).
- vi) 68KCM front-bus and address decoding logic. The address decoding logic decodes the address bus of the MC68000 and decides which device (if any) on the interface card has been addressed. So the devices are all addressed like memory locations by the MC68000, through the front-bus.

5. NMR SET-UP PERFORMANCE

The speed of the NMR set-up is measured with a 4 MHz version of the MC68000; 8 MHz chips are available, and in the future even faster ones (10 MHz already and 12 MHz next year, according to Motorola). With the prototype program, 200 frequency sweeps, each 400 steps, with 16 μ s delay time for the signal to settle, are executed in 7.9 s, including normalization of the data. This means that the processor performs every step in 98.7 μ s. When the program is optimized, i.e. it also calculates during delay times (signal settling time and ADC conversion time), the time per step can be reduced to 60-70 μ s. The minimum step time for the hardware is between 30 and 40 μ s, which can easily be reached with the 8 MHz version of the MC68000. Figure 5 shows the base lines and TE signals (0.25% polarization) taken with this NMR set-up, which demonstrate the quality of the measurement. The signal of fig. 5e took 39.5 s to average with 1000 sweeps of 400 steps using the prototype program. The signal height corresponds to a 10^{-3} change in the impedance of the tuned circuit. The surface area of a signal of this quality can be determined with about 0.1% statistical accuracy.

6. POSSIBLE APPLICATIONS AND EXTENSIONS OF THE 68 KCM

6.1 Data compression

The structure of a data-taking system like CAMAC is usually a tree structure, with a computer at the top, as shown in fig. 6. The maximum speed of the data is limited by how fast the CAMAC bus can transfer the data from a module to the computer. With one or more 68KCMs the data can be preprocessed and compressed before it is sent. This makes the CAMAC bus speed less critical for the total speed of the system. Also the data taking becomes more versatile, because the processor system is programmable and modular, and has large interfacing capabilities.

6.2 NMR multi-channel operation

In large targets the polarization has to be measured in different parts [the largest system at CERN has 8 channels^{*)}]. One processor could control, for example, four NMR interfaces, which would simultaneously measure the polarization in different coils. In comparison with a single-channel measurement, this would not slow down the measurement cycle too much, because the speed is more limited by the necessary delays ($\approx 15 \mu\text{s}$ RF level stabilization, $12 \mu\text{s}$ ADC conversion) than by the software. The memory capacity can easily be increased by a memory module, which would connect to the front-bus.

6.3 Intelligent interfacing

This CAMAC processor has the potential to control the present NMR set-up in a more complex way. For instance, to compensate for the small changes which occur in the RF level of the Rockland frequency synthesizer at each frequency step [figs. 5a and c], a fast DAC may output a compensating voltage to the level control. The gain and offset of an amplifier before the ADC could also be controlled, in order to use the maximum dynamic range of the ADC.

^{*)} A report describing this system, by G. Court et al., is in preparation.

We plan to use the processor module in the future for measuring low temperatures with resistance sensors, and for determining $^3\text{He}/^4\text{He}$ isotropic concentrations from an acoustic transducer output. In both of these applications a periodic calibration cycle must be performed, in order to maintain maximum accuracy.

The 68KCM would be ideally suitable for interfacing dipole and quadrupole mass spectrometers, and RF measuring instruments such as complex network analysers, spectrum analysers, frequency counters, and so on. Fast data links in between computers could also be driven by the 68KCM.

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Figure captions

Fig. 1 : Q-meter NMR circuit.

Fig. 2 : NMR polarization measurement set-up.

Fig. 3 : Block diagram of the MC68000 CAMAC microprocessor system (68KCM).

Fig. 4 : Block diagram of the 68KCM NMR interface.

Fig. 5 : a) Base line (1000 sweeps, 400 steps, 40 μ s signal settling time).

Note the regular step structure superimposed on the Q-meter parabola, due to residual AM of the synthesizer. The horizontal frequency axis starts at 107.500 MHz and ends at 107.900 MHz;

b) Base line subtracted base line, as (a), showing system stability, noise and residual RF transients;

c) Unsubtracted NMR signal, as (a), 0.25% polarization;

d) Base line subtracted NMR signal of (c);

e) As (d), but with 16 μ s signal settling time.

Fig. 6 : Block diagram of tree structure data taking.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

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