NEW DIGITAL NMR SYSTEM FOR AN OLD ANALYZING MAGNET

Z. Kormány, I. Ander, Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), P. O. Box 51, H-4001 Debrecen, Hungary

Abstract

The analyzing magnet of the ATOMKI cyclotron measures the beam energy with high precision and can lower its energy spread to ~5x10^{-4}. The highly stable magnetic field is achieved by NMR-feedback in the control loop of the power supply. The original analog system was designed and built over 25 years ago applying mainly obsolete, partly nowadays unavailable components. Maintaining and keeping the system running required increasing efforts every year.

A new digital system has been developed to replace the old one. Except the high-frequency signal domain (HF oscillator and preamplifier) it performs every processing digitally. Its heart is a mixed-signal microcontroller that generates the signals for the probe, measures the amplitude and frequency of the oscillation, evaluates the demodulated signal and controls the power supply. A fast NMR-pulse detection algorithm was developed; as a result the embedded program can perform all measuring, detecting and controlling tasks in real-time.

A PC connects to the controller, sends commands and displays the received signals and status data. The control software allows easy handling of the complete system with nearly automated operation.

INTRODUCTION

The MGC cyclotron is a multi-particle variable-energy machine and the magnetic field of its analyzing magnet [1] has to be set and stabilized between 0.26 and 0.75 T. The corresponding NMR-frequency band extends from 11 to 32 MHz [2].

The original system was built of two main units. The remote one is located near the magnet and contains the HF marginal oscillator with the external NMR-coil and the modulating coil, both placed inside the magnet gap. The required frequency band cannot be covered as a whole and it is divided into two regions; the crossover frequency is around 19 MHz. Selecting the higher band is implemented by switching an additional inductance in parallel into the tank circuit of the HF oscillator. Tuning to the required NMR frequency within one band is accomplished by a DC motor and gear driven rotating capacitor. The tank circuit has a varicap diode as well for fine tuning of the frequency. The oscillation amplitude is controlled by a DC voltage coming to the remote unit via the RF cable which is used to send the HF signal to the central unit.

The central unit is located in the control room of the cyclotron. It contains manual control elements, signal generator and power supplies to control the remote oscillator and the modulating coil. It also has analog electronics to process the HF signal coming from the remote unit. The detected NMR-pulse is displayed on oscilloscope screen and the measured error voltage is used to stabilize the magnet power supply.

NEW SYSTEM HARDWARE

NMR systems typically apply low frequency magnetic field modulation for repetitive generation of the resonance effect. Advanced digital electronic modules are able to produce all the required control signals and to measure and process the generated resonance signal [3].

The architecture and the remote unit from the original system have been kept, but a completely new central unit has been developed. The new central unit applies mainly digital signal processing. The only exception is the high frequency domain of the incoming signal. This signal is first split into two paths. One is used for the accurate measurement of the frequency of the HF oscillation. The other is the main signal route where the amplitude modulated signal of the marginal oscillator is processed. First this signal is amplified in order to perform the amplitude demodulation efficiently. A Mini-Circuits ZFL-500HLN+ [4] broadband amplifier was applied to get an input level of maximum 16 dBm for the home-built simple detector circuit. The detector provides the demodulated signal which contains only low frequencies determined by the modulating coil driving signal. A second task of the detector circuit is to generate a feedback to the marginal oscillator for amplitude stabilization. This signal is proportional to the difference of the detected HF oscillation amplitude and a reference signal.

The new central unit is built around a mixed-signal microcontroller C8051F041. Its connections with other elements of the system are detailed in Fig.1. On the left side of the microcontroller the interfaces with the remote unit are depicted. For the proper operation of this unit the following signals have to be generated by the controller:

Analog outputs:

- Oscillation amplitude reference signal (*Amp. contr.*)
- Modulating coil driving signal (*Field modul.*)
- Frequency fine tuning signal (*Varicap control*)

Digital outputs:

- Frequency band selection (*Freq. band control*)
- Frequency coarse tuning (*Motor control enable*)
- Frequency coarse tuning up (*Motor control left*)
- Frequency coarse tuning down (*Motor control right*)

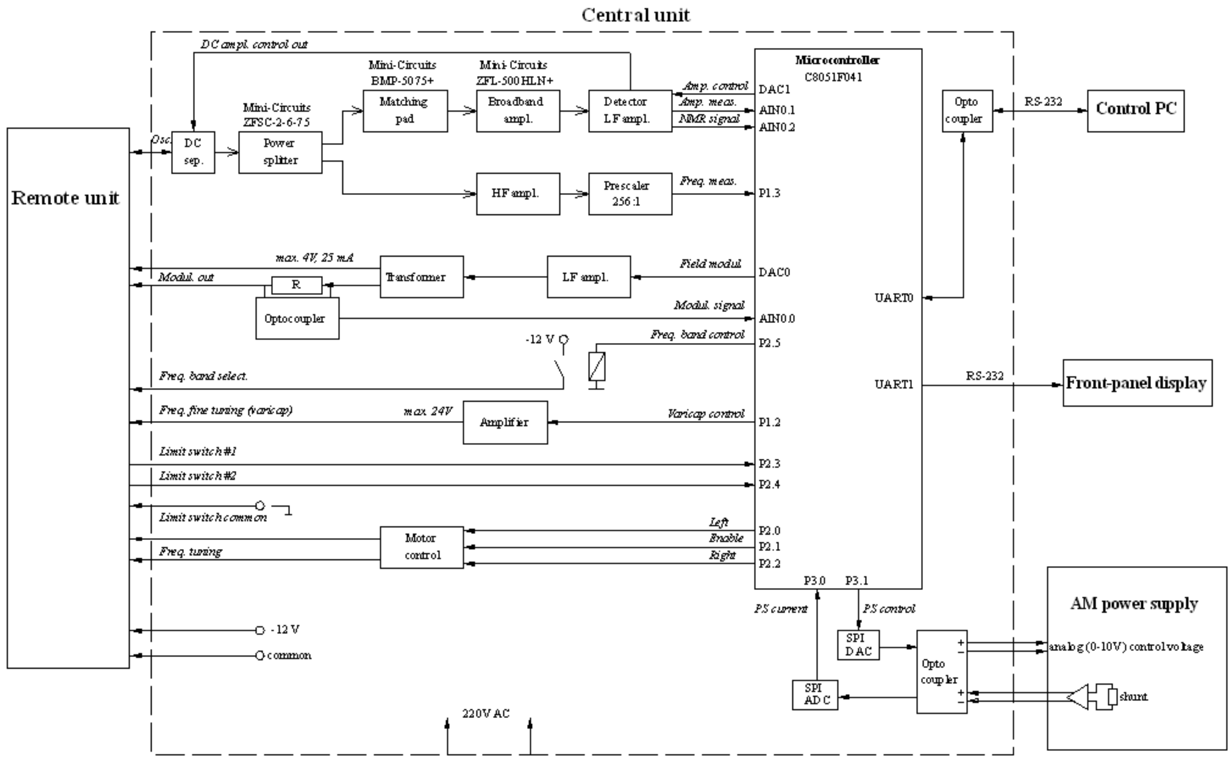

Figure 1: Block diagram of the new central unit with its connections to the rest of the system.

The signals which have to be processed by the microcontroller are coming either directly from the remote unit or are separated from the HF modulated signal by the interface elements:

Analog inputs:
- Oscillation amplitude (*Amp. meas.*)
- Demodulated NMR-signal (*NMR signal*)
- Measured modulating coil current (*Modul. signal*)

Digital inputs:
- Oscillation frequency (*Freq. meas.*)
- Frequency coarse up limit (*Limit switch #1*)
- Frequency coarse down limit (*Limit switch #2*)

The lower right part of Fig.1 shows the interfaces with the analyzing magnet power supply. 16-bit DAC and 12-bit ADC are applied with optocouplers to generate the required 0-10V control voltage for the PS and to measure the actual magnet current.

On the right side of the microcontroller the operator interfaces applied in the new system can be seen. Serial connections are used to render important operation data on the front panel display of the central unit and to connect to the main control PC of the system.

CONTROL AND SIGNAL PROCESSING

The time base for signal processing in the embedded control program of the microcontroller is the period length of the field modulating signal. In order to accurately evaluate the narrow NMR-pulses, 200 samples are taken during one period. The sampling rate was set to 22 kHz, resulting in 110 Hz modulation frequency. This rate allows continuous measuring without overload and is fast enough to provide real-time control for the magnet power supply.

Evaluation and processing of the sampled demodulated signal is carried out simultaneously with sampling. A simple but efficient pulse detecting algorythm assures that in the end of every period the program can determine if a real NMR-pulse was found. The algorythm is based on the fact that NMR-pulses appear in pair during one modulation period and the sum of their indices is constant. The efficient detection is greatly supported by the low noise level in the demodulated signal as seen in Fig. 2.

The value of the magnet current is correct when the two pulses are hovering at the zero crossings of the modulating sine wave. In this case the difference of their indices is equal to the half of the period length. Any deviation from this value is proportional to the current error and is used to adjust the magnet current to eliminate it.

The microcontroller with its embedded code makes a stand-alone system. It can keep the magnet current stabilized without operator intervention. Moreover, it can search alone for the NMR-resonance and tune the magnet current until it is found. The operator control program is running on a Windows PC. It allows operating the system

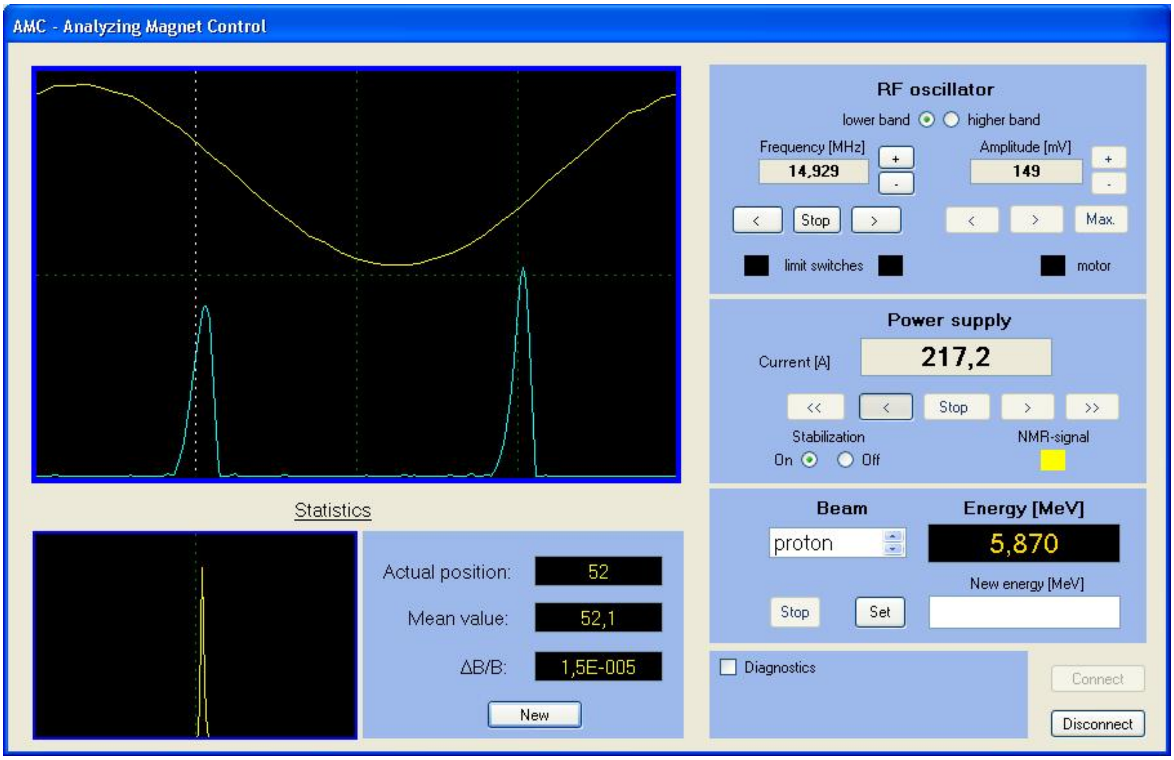

Figure 2: Operator interface of the new system with the measured field modulating current (sine wave) and the detected NMR-pulses. The resonances occur at the zero crossings of the modulating signal proving the right setting of the main magnetic field of the analyzer. The distribution of the measured pulse positions is shown in the lower left corner of the display. The program determines the uncertainty of the stabilized magnetic field from the measured actual position distribution of the pulses.

in different ways. The user can either manually set any parameter (oscillator frequency, amplitude and magnet current) or can simply define the used beam (particle type and energy) and request the system to tune automatically.

The front panel display shows the actual system status properly even if the operator control program is not running. It displays the HF oscillator frequency value, the oscillation amplitude and the actual current flowing in the coils of the analyzing magnet. It shows the status of communication with the control PC. The detection of the NMR-pulses and the proper operation of the feedback circuit are also reflected.

CONCLUSIONS

The new system has been in operation for over a year. The applied digital signal processing proved to be a very successful and cost-effective remedy for our field stabilization problems caused by aging analog electronics. The designed hardware and software elements build up a generally applicable and inexpensive solution for creating NMR-feedback in high precision magnetic field stabilization systems.

The new system has made work with our old analyzing magnet really easy. At the same time not just reliability and easiness of operation have been improved with the implemented digital signal processing. Significantly better values of field stability are measured as well. Typical magnetic field fluctuations in the analyzer are now well below the required $5x10^{-5}$ level.

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