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DEVELOPMENT OF A MEASURING CHANNEL FOR LOW CURRENTS INTEGRATING ON ANALOG DEVICES COMPONENTS AND ARDUINO MODULES FOR PHYSICAL EXPERIMENTS

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The development of low currents measuring channel necessary to ensure the operation of the experimental complex based on a linear electron accelerator with energy of 30 MeV at IHEPNP NSC KIPT for fundamental and applied research on the interaction of high-energy electrons with amorphous and single-crystal structures is described. The channel makes it possible to measure currents of the order of 0.1 nA and less, with an accuracy better than 0.1 %, and is connected to an upper-level computer via the USB interface.

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INTRODUCTION

The essential requirement to measure low current (charges) values arises during a number of nuclear physics experiments. For example, to ensure the operation of an experimental complex based on 30 MeV IHEPNP NSC KIPT linear electron accelerator for fundamental and applied research on the interaction of high-energy electrons with amorphous and single-crystal structures. It is necessary to measure currents of the order of 0.1 nA or less, with an accuracy better than 0.1 %. The setup and planned experiments are described in more details in [1, 2]. In addition, to ensure the operation of the accelerator, during the experiment, a channel for constant current control from the Faraday Cup and several ionization chambers is required. The absolute values of these currents can range from 10 nA to 100 μA. Traditionally, charge-code converters are used to carry out such measurements. The practical implementation of such a converter is described in [3]. This converter has high sensitivity and linearity, but, unfortunately, has a number of disadvantages. In particular, it requires very stable power supplies and has significant temperature drift. In addition, there are certain inconveniences of connection this converter with a computer to automate the measurement process.

Taking into account the experience with charge-code converters, it was decided to use integrating current-voltage converters, followed by digitization of the output signal using an analog-to-digital converter (ADC) and preliminary processing of digital data by a microprocessor. Such architecture of the measuring channel allows pre-processing of data and simplifies communication with an upper-level computer.

1. INTEGRATING CURRENT-VOLTAGE CONVERTER FOR MEASURING SMALL CURRENTS

To measure the value of the secondary emission current or the current of accelerated electrons, a universal integrating current-voltage converter has been developed and manufactured. The use of modern operational amplifiers with low input currents (on the order of 0.01 nA) made it possible to develop a universal device suitable for accelerator experiment measurements with continuous and pulsed beams. The converter has two independent measurement channels. The conversion factor of the first channel is 1 V/μA, the second channel is 1 V/nA. The range of measured currents for the first channel is from +5 μA to -5 μA, for the second channel: +5 nA to - 5 nA. The Atmega328 microprocessor, which is part of the block, is used to process the output signals of the converter and communicate with the computer. The software is written applying the WinAVR package. Data transfer between the computer and the unit is carried out via the USB interface. The structural diagram of the converter is shown on Fig. 1.

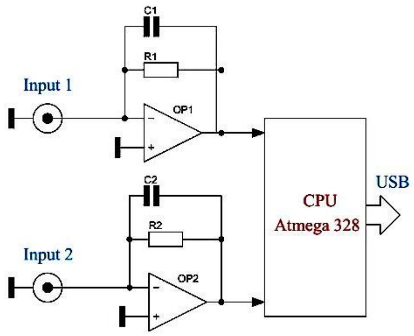

Fig. 1. Structural diagram of the integrating converter

The converter has two measuring inputs (Input1, Input2). For direct current, the output voltage of the operational amplifier OP1 is determined by the equation $U_{out} = -R_1 \cdot I_{in}$. The time constant of the feedback circuit (integration) is equal to the product of R_1 and C_1. This value is chosen equal to 1 second for the convenience of converting current into charge (charge measurement mode). For pulsed signals, the duration of which is much less than the constant integration time, i.e. $T_i << 1$ s, the inverter output voltage will be $U = Q/C_1$.

To measure currents of the order of units of nanoamps, the resistance feedback value reaches values from hundreds of MegaOhms to units of GigaOhms. To reduce the measurement error, this resistor consists of several precision ones made on the basis of metal oxide films in the SMD version. Sufficiently stringent requirements are imposed on the integrating capacitor C_1 in terms of the leakage current (less than 0.1 nA) and the magnitude of the dielectric absorption. It should be noted that in order to ensure high metrological characteristics of the transducer, it is necessary to fulfill a number of design and technological requirements (selection of elements of the feedback circuit, design R_1, etc.). Further improvement of the characteristics of the converter can be achieved by using the gated mode of operation; however, this entails a significant complication of the circuitry of this device.

Schematic diagram of the converter is shown on Fig. 2. The input stage of the converter is made on an operational amplifier (op-amp) AD711 [4] with an input leakage current of about $1.5 \cdot 10^{-11}$ A. This is followed by a scaling amplifier stage with a variable gain, also on the op-amp AD711. Thus, the conversion factor of the circuit can change by a factor of 10 (10^{-8} or 10^{-9} A/V).

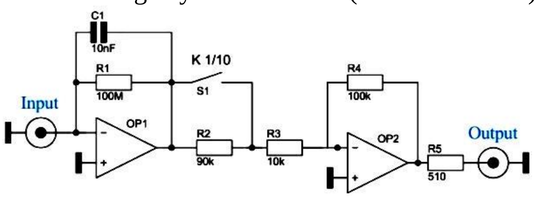

Fig. 2. Schematic diagram of the converter

As an analog-to-digital converter (ADC), an internal microprocessor converter is used, which is part of the Atmega328 CPU block. The ADC has 10 digits, which provides measurement accuracy better than 0.1 % at the maximum input signal. The structural diagram of the Atmega328 CPU block is shown on Fig. 3. The CH341 chip is used as a USB interface converter.

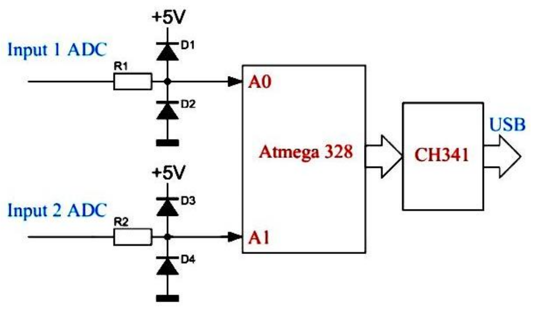

Fig. 3. Structural diagram of the block CPU Atmega328

The signals from the outputs of the integrating converters are fed to the analog inputs A0 and A1 of the Atmega328 through resistors R1, R2 and diodes D1-D4, which protect the ADC inputs from level overload and reverse polarity. The program written in the Atmega328 cycles through the ADC makes ten measurements for each input and averages the measurement results, after which the data is transferred via the USB port to the PC for further processing. The software is written applying the WinAVR package under the General Public License.

2. DISADVANTAGES OF THE CONVERTER AND THE POSSIBILITY OF FURTHER MODERNIZATION

When conducting experiments for the pulsed accelerator beam operation with a large pulse duty cycle, an additional measurement error occurs due to the integration of noise signals. The reason for this problem is shown on Fig. 4.

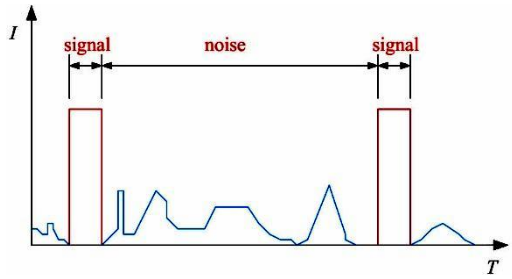

Fig. 4. Illustration of the presence of a noise signal

Between the pulses of the useful signal (*signal*) there are noise pulses (noise). Their presence is due to the operation of the accelerator high-frequency power supply systems, the temperature control system operation, etc. Thus, to increase the accuracy of measurements, it is necessary to use a gated current-voltage integrating converter, which allows measurements to be taken only at the moment of the presence of a useful signal. In addition, to increase the accuracy of measurements, it is possible to use an external ADC of a larger capacity, connected to the CPU via a digital data transmission bus (SPI, I2C). It is possible to use an external 16-bit ADC based on the miniature ADS1115 chip [5], which has an I2C interface and four single-ended or two differential inputs. Programmable conversion frequency is 8…860 conversions per second. As a microprocessor unit, it is possible to use the ready-made Arduino Nano module [6, 7] and program it in the Arduino IDE. This will significantly reduce the development time of printed circuit boards and software.

3. STROBE INTEGRATING CURRENT-VOLTAGE CONVERTER

To implement the gated mode of operation of the current-voltage converter, it is necessary to install an electronic switch at its input, which will disconnect the converter input from the measured signal in the intervals between accelerator current pulses. Such converters are produced in integrated design, for example, *the IVC102* microcircuit [8]. The design of the converter on discrete elements has one, but very significant, advantage over the integral design. This is its maintainability. The fact is that when providing a physical experiment, various emergency situations may occur, leading to damage to the input of the converter. A simplified diagram of the control unit and the input key control pulse shaper is shown on Fig. 5.

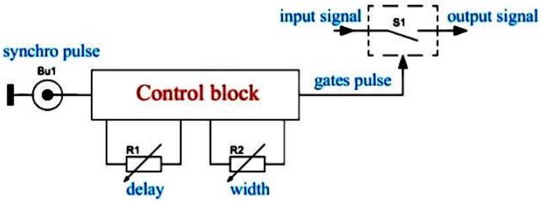

Fig. 5. Simplified diagram of the shaper

The accelerator synchronization pulse (synchro pulse) is fed to the input of the control unit, which generates the input key control pulse (gates pulse) *S1*. The integral switch ADG419 [9] was used as an input key.

The measured input signal is fed to the ADG419 input, and the signal from its output (output signal) is fed to the input of the current-voltage converter. The shaper operation algorithm is illustrated on Fig. 6. Using variable resistors *R1* and *R2*, it is possible to adjust the delay of the key control signal relative to the synchronization pulse and its duration. Thus, only the measured signal will be fed to the input of the transducer, and the noise will be cut off.

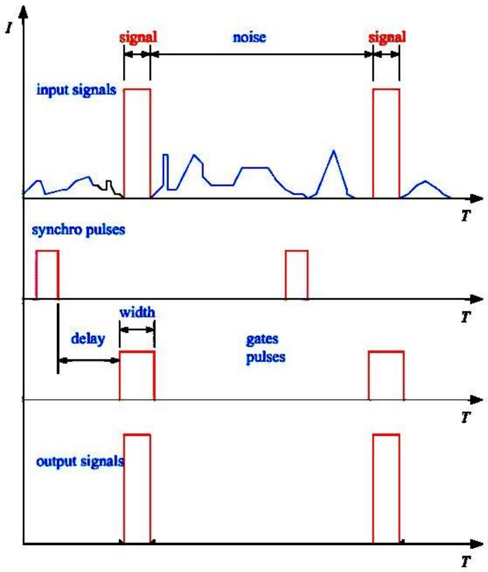

Fig. 6. Algorithm of the shaper

A simplified circuit diagram of the shaper is shown on Fig. 7. The 74HC4538 microcircuit in standard switching was used as single vibrators. BOCHEN WXD3-13 multi-turn precision resistors are used as resistors R1 and R2.

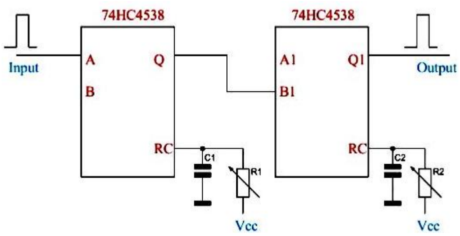

Fig. 7. Simplified circuit diagram of the shaper

As is clear from the above diagram, the accelerator clock triggers the first single vibrator, which generates a pulse, the duration of which depends on the values of R1 and C1. On the trailing edge of the pulse at the output Q, the second single vibrator is started, the duration of which depends on R2, C2.

4. PROCESSING UNIT OF THE MEASURING CHANNEL

The block includes an *ADC*, an Arduino Nano V3.0 microprocessor module, a liquid crystal display and operating modes controls. The structural diagram of the block is shown on Fig. 8.

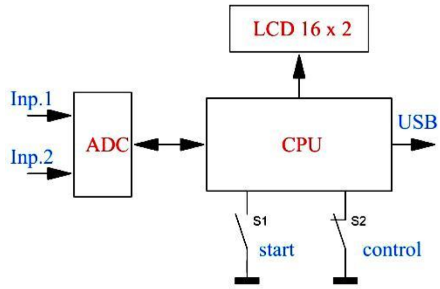

Fig. 8. Structural diagram of the processor unit

Input analog signals from current-voltage converters are fed to the inputs Inp.1, Inp.2 and converted into digital data using ADC ADS1115. Further processing of the digital signal takes place in the CPU Arduino Nano V3.0. To improve the accuracy of measurements, a series of measurements is made for each analog input, followed by averaging, in addition, the processing possibility of the module is quite enough to carry out the simplest statistical processing, which can further increase the accuracy. The operation of the unit is possible in stand-alone mode and as part of an experimental complex of equipment controlled by an upper-level computer. The choice of operating mode is made by switch S2 (control). In offline mode, measurements are taken once, by pressing the S1 (start) button, the results are displayed on a liquid crystal display (LCD). When working as part of a complex of equipment, measurements are made by a control signal from an upper-level computer, data exchange between the CPU and computer occurs via a standard USB interface.

CONCLUSIONS

With relatively small material costs, it was possible to create a measuring channel that provides measurement of currents in the range from *0.1 nA* to *10 μA*, with an accuracy of better than *0.1 %* (not counting the initial part of the *ADC* scale). Ways are being considered to further upgrade the measuring channel to further improve accuracy and temperature stability.

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РОЗРОБКА ВИМІРЮВАЛЬНОГО КАНАЛУ ІНТЕГРУВАННЯ МАЛИХ СТРУМІВ НА ЕЛЕМЕНТНІЙ БАЗІ ФІРМИ ANALOG DEVICES І МОДУЛЯХ ARDUINO ДЛЯ ФІЗИЧНИХ ЕКСПЕРИМЕНТІВ

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Представлено розробку вимірювального каналу малих струмів, необхідного для забезпечення функціонування експериментального комплексу на базі лінійного прискорювача електронів з енергією 30 МеВ ІФВЕЯФ ННЦ ХФТІ для фундаментальних та прикладних досліджень щодо взаємодії електронів високих енергій з аморфними та монокристалічними структурами. Канал дозволяє вимірювати струми порядку 0,1 нА і менше, з точністю не гірше 0,1 %, і має зв'язок з ЕОМ верхнього рівня за інтерфейсом USB.