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AN EMBEDDED BEAM DIAGNOSTIC ELECTRONICS FOR 230 MeV SUPERCONDUCTING CYCLOTRON RADIAL PROBE AND SCANNING WIRES

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Abstract

For the 230 MeV superconducting cyclotron, once again, the differential radial probe has been proven to be crucial for the beam commission procedure. It can provide various information about the particles inside the cyclotron, such as the vertical position, the relative intensity as well as the oscillation frequency and radius, etc. In practice, however, the electronics system suffered from the leaking alternating RF field as well as the static magnetic field. Besides the EM shielding, an absorptive high-frequency filter has been included as the first element of the readout electronics. A high dynamic range readout electronic unit has been included to adapt to the fluctuation of the beam in the hole commissioning phase. The electronics box is designed as a network-attached embedded device so that it can be powered by a POE switch and transmits measurement results via MODBUS protocol. A dedicated digital signal processor and calibration units are also included, together with the ADCs, to facilitate the daily calibration process. The same electronics are used for the beamline wire scan system to determine the position of the beam, with a small improvement at a lower range. The design of this multi-purpose beam diagnostics electronics will be reviewed in this paper, together with several measurement results.

INTRODUCTION

The China Institute of Atomic Energy (CIAE) is developing a 230 MeV superconducting cyclotron, a commercial prototype that can be used for proton therapy, which is designed to induce energy of 230 MeV and beam current over 300 nA [1, 2]. During the beam commission procedure, the radial probe can measure beam parameters from a radius of 300 mm to 850 mm inside the cyclotron. It can provide the intensity and the alignment information of the beam. The material of the head of the radial probe is tungsten, the beam will deposit on the head, so it's an interception measurement method. The drive unit of the radial probe is mounted on a stand and the rod drives the head, which is fixed to the drive unit. The drive unit drives the head in a reciprocating motion inside the cyclotron and a potentiometer determines the position of the head movement [3, 4]. Scanning wires is a non-intercepting beam diagnostic method used to measure beam position on the beamline [5]. The probe head used by CIAE is a double-wire structure with an angle of 90°. The material of the measuring strip is a copper alloy with a width of 5 mm and a thickness of 0.1 mm.

Since the beam current may work in the case of low intensity and high intensity, CIAE designed a beam diagnostic electronics system. The existing diagnostic electronics for 230 MeV superconducting cyclotron radial probe and scanning wires can measure currents from 1 pA to 10 mA range. However, its measurements are not continuous, and the readout electronic unit is based on a trans-impedance amplifier that requires manual switching of the different feedback resistors depending on the signal being measured. The data processing module of the existing wire scan system is based on PLC, and the sampling rate (2 Hz) of the system is also low.

DESIGN OVERVIEW

The new embedded electronics under development will eventually replace the existing boards used for the initial phase of the 230 MeV superconducting cyclotron project. The new electronics allow for continuous, high dynamic range measurements with higher sampling rates than previous designs.

The new electronics box is designed as a network-attached embedded device so that it can be powered by a POE switch and transmits measurement results via MODBUS protocol. To reduce electromagnetic interference, an absorptive high-frequency filter (RLC filter) has been included as the first block of the readout electronics. The core part of the electronics is the high dynamic range readout electronics unit. The board has 3 I/V conversion channels, each including a wide dynamic range I/V converter and a weak signal I/V converter. The 4 channels (3 I/V conversion channels and a position signal channel) are digitized using AD7665 16-bit ADCs, and then further processed on the DSP, Butterworth filter is applied to process the raw data. Embedded SRAM is used for the temporary storage of measurement data, while a calibration unit facilitates the daily calibration process. Triaxial connectors are used to transmit beam current signals to adapt to weak signal detection. A protection circuit (gas discharge tube and JFET) is set before the readout electronics unit to prevent accidental damage.

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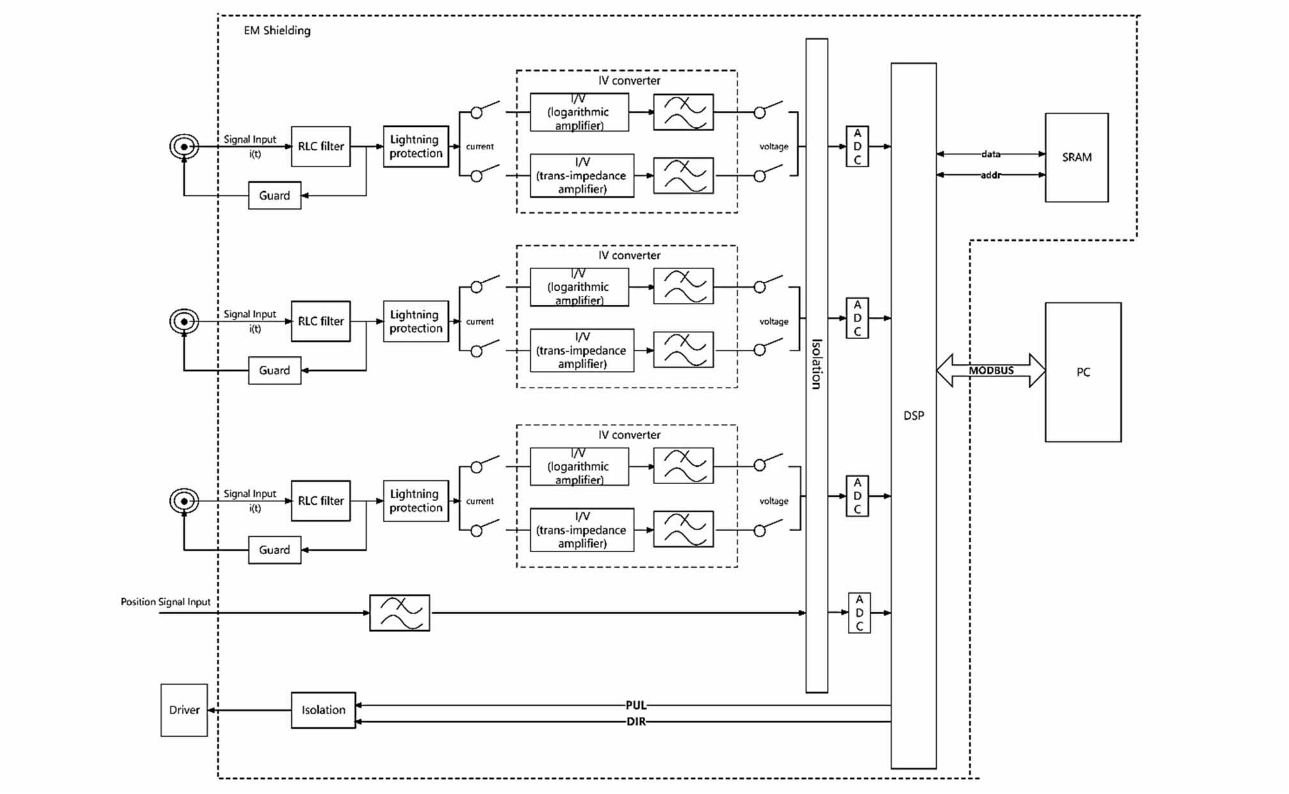

Figure 1: Design of the beam diagnostic electronics.

READOUT ELECTRONICS FOR HIGH DYNAMIC RANGE CURRENTS

The Basic Principle of I/V Converters

The principle of the wide dynamic range I/V converter is based on logarithmic amplifiers. In the linear domain, a high dynamic range signal will generally cause the existing ADCs to fail to work properly, logarithmic amplifiers can effectively solve this problem. The basic schematic of the logarithmic amplifier is shown in Fig. 2, using the logarithmic relationship between the emitter voltage and the collector current of a transistor [6].

$$V_O = -\frac{kT}{q}\ln\left(\frac{I_{in}}{I_S}\right), \tag{1}$$

where k is the Bolzmann's constant ($1.38 \times 10^{-23} J/K$), T the temperature in K, q the electronic charge ($1.6 \times 10^{-19} C$), and I_S a reference current depending on the temperature (Eq. (1)).

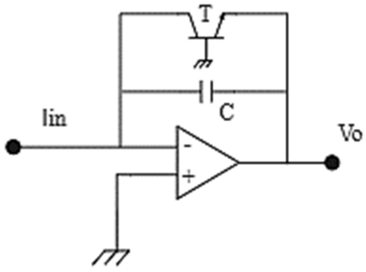

Figure 2: Basic schematic of the logarithmic amplifier.

Using the logarithmic property, when the input signal is weak, the input and output are approximately linear and the system is highly sensitive; when the input signal increases, the input signal varies over a wide range while the output signal varies less.

The principle of the weak signal I/V converter is based on a trans-impedance amplifier (see Fig. 3).

$$V_O = -I_{in} \times R, \tag{2}$$

where R is a high-resistance resistor and the input impedance of the op-amp is much higher than R [7] (Eq. (2)). I/V conversion sensitivity increases as the value of the resistor R increases.

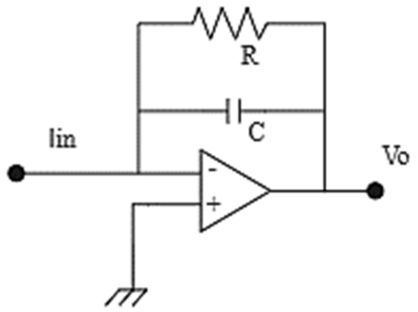

Figure 3: Basic schematic of the trans-impedance amplifier.

Design of I/V Converters

The high dynamic range readout electronic unit contains the I/V converters for 3 channels, using relays to select different I/V converters. The wide dynamic range I/V converter uses commercially available logarithmic amplifiers AD8304 and this module allows current from 100 pA to 5 mA to be measured. Low input bias current ($\leq 20fA$) amplifier ADA4530-1 used in the weak signal I/V converter. The module can measure currents from 100 fA to 60 pA when the feedback resistance is taken to be 100 GΩ.

The I/V converter is followed by a low-pass filter with a cut-off frequency of 16 kHz which, in addition to filtering, provides further gain to the I/V converter output signal. For improved measurement accuracy, a metallic enclosure shields the electronics from external electromagnetic interference. Triaxial Cables are used to transmit beam current signals, besides that the electrical ground of the readout electronic unit (I/V converter, filter) and the data processing module (DSP, ADCs, SRAM) are separated to avoid ground loop problems. The offset and gain of each I/V channel will be manually calibrated separately.

Figure 4: The beam diagnostic electronics for 230 MeV superconducting cyclotron radial probe and scanning wires.

Experimental Results

Using the DC precision current source (Keithley 6220) to simulate the measurement signal. The results of the wide dynamic range I/V converter are shown in Fig. 5. The figure shows input currents from 0.1 nA to 5 mA, corresponding to output voltages from 0.5 V to 5 V. It can be seen that the input current is logarithmically related to the output voltage, and the I/V converter sensitivity is high when the input current is weak.

The feedback resistance of the weak signal I/V converter is 100 GΩ and a measured conversion sensitivity of 10^{11} V/A.

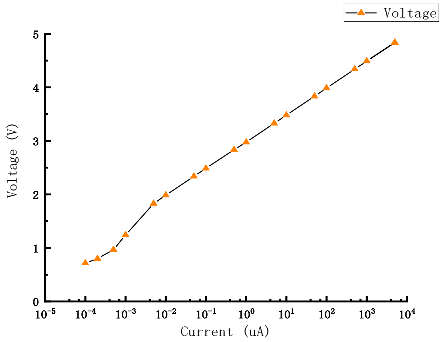

Figure 5: The results of the wide dynamic range I/V converter.

CONCLUSION

The new embedded electronics contain both logarithmic amplifiers and trans-impedance amplifiers as I/V converters for high dynamic range signal measurements, enabling continuous measurement of currents from 100 pA to 5 mA and transimpedance amplifiers with a sensitivity of 10^{11} V/A. The electronics are designed to reduce external electromagnetic interference through electrical isolation and shielding enclosures. Embedded ADCs, SRAM and a DSP effectively increase the sampling rate. The design is suitable for the radial probe and the wire scan systems.

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