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New data acquisition system for beam loss monitor used in J-PARC main ring

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ABSTRACT

A new data acquisition system has been developed continually as a part of the development of a new beam loss monitor (BLM) system for the J-PARC main ring. This development includes a newly designed front-end isolation amp that uses photo-couplers and a VME-based new analog-to-digital converter (ADC) system. Compared to the old amp, the new amp has a 10 times higher conversion impedance for the input current to the output voltage; this value is 1 MΩ. Moreover, the bandwidth was improved to from DC to 50 kHz, which is about two orders of magnitude greater than the previously used bandwidth. The theoretical estimations made in this study roughly agree with the frequency response obtained for the new system. The new ADC system uses an on-board field-programmable gate array chip for signal processing. By replacing the firmware of this chip, changes pertaining to future accelerator upgrade plans may be introduced into the new ADC system; in addition, the ADC system can be used in other applications. The sampling speed of the system is 1 MS/s, and it exhibits a 95 dBc spurious-free dynamic range and 16.5 effective number of bits. The obtained waveform and integrated charge data are compared with two reference levels in the ADC system. If the data exceeds the reference level, the system generates an alarm to dump the beams. By using the new data acquisition system, it was proved that the new BLM system shows a wide dynamic range of 160 dB. In this study, the details of the new data acquisition system are described.

1. Introduction

The J-PARC main ring (MR) has been delivering two types of high-power proton beams to two different experimental facilities; bunched beams to the neutrino production target for the T2K experiment [1,2] and slowly extracted un-bunched beams to the hadron experimental facility [3,4]. These two types operations are called fast extraction (FX) operation and slow extraction (SX) operation, respectively. Each operation cycle, which includes one sequence of injection, acceleration, and extraction, typically lasts 2.48 s for FX and 5.52 s for SX at present. The designed beam power of the J-PARC MR was 750 kW [5,6], and the upgrades currently underway will increase the beam power to 1.3 MW by shortening the operating cycle of the accelerator [7].

The beam loss monitor (BLM) system is one of the most important beam diagnostic tools for the J-PARC MR. In the J-PARC MR, proportional-type gas chambers (pBLMs) are used as the main detectors. The maximum gas gain of the pBLMs is 2E4 at a bias voltage of −2.0 kV; the details of the pBLMs are described elsewhere [8–10]. The capacitance of the pBLM is 11 pF. The initial charge induced by a beam loss is amplified by the gas gain, and the output current divided by the gas gain can be used as the beam loss signal. By changing the bias settings, a wide dynamic range can be covered. However, an increase in the output current leads to a decrease in the gas gain [11]; for example, output DC currents of 1 and 10 μA result in 4% and 40% decreases in gain, respectively, for a bias voltage of −1.6 kV. This gain degradation is due to the space charge effect ascribed to the ionized positive ions in

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the gas; because the mobility of an ion is lower than that of an electron, the ions remain in the gas after all electrons have been captured at the anodal wire. This means the pBLMs are likely to underestimate beam power losses, especially in the injector and collimator, and SX sections, because large beam losses are inevitable in these sections.

An air ionization chamber (AIC) is an ion chamber that employs a double shielded 20D type coaxial cable. A corrugated Cu pipe acts as the inner shield core, while spiral polyethylene acts as the insulator [12]. The center Cu pipe picks up the charge, while the bias voltage is applied to the corrugated Cu pipe. The outermost Cu tape shield is grounded. The average length of a long-type AIC is 84 m long. Nineteen long-type AICs cover the length of the J-PARC MR tunnel, and they are installed on the cable rack running on the outside wall of that tunnel. The capacitance of the AIC is 74 pF/m. The distance between the detectors and the center of the beam duct is 3 m. The long-type AICs were calibrated using intentional beam losses in the injection beam at the collimator units and in arcs A and B. The beam losses were controlled using the local bump orbit. The long-type AIC installed in the collimator section outputs 13.3 nC for a beam loss of 1E11 3 GeV protons at the collimators. The efficiency of the long-type AIC in the collimator section, which is defined as the ratio of the output charge to the beam power lost, is therefore 1/3.6 μC/kJ, while in the arc sections, it is 1/8.9 μC/kJ on average.

The 216 pBLMs and the 19 long-type AICs were incorporated in the old BLM system. The system was designed to meet two requirements. First, it was expected to sense intensive beam losses and send an alarm signal to the machine protection system (MPS). This signal prompts the MPS to trigger a kicker magnet system that dumps the beams under 100 μs [13]. This protects the magnets and other equipment from severe damage due to beam losses. Second, it was expected to determine the position, intensity, and timing information related to any beam loss. This information can subsequently be used to tune the accelerator components, even when the beam intensity is approximately 1% of the designed intensity.

The new BLM system has been designed to meet these original conditions along with a few new requirements. We have modified a few of these items following testing of the system with various beam tunings from the items listed in [14]. The first new condition is that the acceptable beam power losses in the MR must be set to 0.5 W/m in the arc sections, 2 kW in the collimator section, 7.5 kW in the SX section, and 1.125 kW in the FX section [6,15]. As of now, the strongest signal has originated from a detector installed in the collimator section; these losses are caused by injection mismatches and by imperfections in the momentum tracking of the bending magnets after start of the acceleration. Numerical calculations show that expected radiation exposure to the pBLM is about 0.053 Gy/cycle [8] in case of 2 kW uniform beam power loss in the collimators, where a cycle means an operation cycle of the MR. These power losses induce an initial charge of about 14 μC/cycle in the pBLM.

The second new requirement is that, independent of the beam power loss, the activation levels of the components should remain within the limits that allow workers to perform hands-on maintenance activities. This means that each device should display the levels that should not be exceeded for their maintenance operations. Furthermore, these activation levels should be measured after the beam has been turned off [16]. As a result, residual doses as low as 100 μSv/h must be detected. This activation level induces an initial charge of about 1.2E−5 μC/cycle in the pBLM. To cover such a wide range of signals, from the highest level of 14 μC/cycle for a beam power loss of 2 kW in the collimators to the lowest level of 1.2E−5 μC/cycle for residual dose measurement after beam stoppage, the monitoring system must have a dynamic range of 120 dB.

The final new condition is that the bandwidth (BW) needed to monitor beam losses occurring at every turn is set to DC to 200 kHz. To study head–tail instability, the system must be able to detect high-frequency signals, such as 100 MHz [17].

In the new BLM system, three types of detectors have been incorporated to improve its dynamic range: pBLMs, 1-m-long short-type AICs (sAICs), and long-type AICs. The 216 pBLMs and 53 sAICs (only in the straight sections of J-PARC MR) are mounted at each quadrupole magnet (QM), and they are set to be 360 mm away from the QM surface and 848 mm from the center of the beam duct. The maximum output current and the sensitivity of the sAICs were checked using gamma rays from a strong ^{60}Co gamma source. The data showed linear response up to 10 μA within an uncertainty of about 10%. The sensitivity was 11 μC/Gy [14]. The designed maximum output current from the sAIC was set to 10 μA.

In addition to the detector system upgrades, a new front-end amp circuit was developed to improve both the conversion impedance and the BW of the front-end amp. Moreover, the ADC system was upgraded to enhance its performance and flexibility.

The new BLM system has been operating since last summer. High-level radiation from the collimators has been measured by the sAICs. The output charge from the sAIC is about 0.58 μC/cycle for the case of uniform beam power loss of 2 kW in the collimators. If the loss were to occur within 0.1 s just after start of the acceleration, the output current would be about 6 μA, which is lower than the designed maximum output current of 10 μA. The pBLMs can cover a wide range of activations induced by beam power losses along the entire MR ring by changing the bias setting.

The output current waveforms and integrated charge data were obtained using the new data acquisition system. To measure the residual doses after beam stoppage, the maximum bias voltage of −2 kV was set for the pBLMs, and only the integrated charge data were processed. The typical integration time set for this measurement was 1.6 s. The minimum dose rate measured after beam stoppage was 0.01 μSv/h which corresponds to the initial charge of 1E-9 μC/cycle.

At each bias setting, the dynamic range was about 80 dB in the integrated charge data, and an appropriate bias setting can expand the total dynamic range. The measured integrated charge data suggest that the system can cover a wide range of signals from 0.58 μC/cycle in case of a uniform beam power loss of 2 kW in the collimators down to 1E-9 μC/cycle in case of the residual dose measurements. The net dynamic range is now wider than 160 dB [18].

In the next section, the performance of the original data acquisition system is summarized. Details of the new front-end amp and ADC systems are described in Section 3; Section 3.1 discusses the operating principle of the new front-end amp, Section 3.2 presents the performance of the new front-end amp and Section 3.3 describes the new ADC system.

2. Old data acquisition system

The data acquisition system of the old BLM system is described in [8]. As for the front-end amp, the first input amp was a non-inverted gain amp with a voltage gain of 5; followed by an amp with selectable gains of 1, 10, and 100; and an output buffer amp with a gain of 2. To convert the negative input current into a voltage signal, selectable shunt resistors of 50 and 10 kΩ were inserted between the positive and negative terminals of the first input amp.

The averaged output current from the pBLM was limited to 1 μA. To facilitate the detection of such low-intensity current signals, only the 10 kΩ resistor was used in normal beam operations. The selectable gain used for beam operations was 10 because of the large coupling noise originating from the power supplies of the magnets and the RF system. This setting resulted in an output of only 0.1 V for an input current of 1 μA. The 50 Ω shunt resistor was used to measure the output pulse from the pBLM detectors; this was done to check the soundness of the data acquisition system when the power supplies of the magnets and RF system were turned off.

The front-end amp and ADC systems were situated in local control rooms of the three power-supply buildings to avoid any malfunctions induced by energetic secondary particles and the radiation generated