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DIFFERENTIAL CURRENT TRANSFORMER FOR BEAM CHARGE MONITORING IN NOISY ENVIRONMENTS

H. Maesaka[†, 1], T. Inagaki[1], RIKEN SPring-8 Center, Sayo, Hyogo, Japan
K. Yanagida, H. Dewa, JASRI, Sayo, Hyogo, Japan
K. Ueshima, QST, Sendai, Miyagi, Japan
[1]also at JASRI, Sayo, Hyogo, Japan

Abstract

We designed and produced a new differential current transformer (CT) for electron beam current and charge measurement in noisy environments, such as near a high-power pulse generator. This differential CT has four pickup wires coiled at equal intervals (90 degrees) on a toroidal core. Each coil has two turns and the midpoint of the coil is connected to the body ground so that a balanced differential signal is generated. A beam pipe with a ceramics insulation gap is inserted into the toroidal core to obtain a signal from a charged-particle beam. The four balanced differential signals are transmitted through a Category-6 twisted pair cable and fed into an amplifier unit. The four signals are then summed by the amplifier and digitized by an MTCA.4 high-speed AD converter. We produced differential CTs and installed them into the new injector linac of NewSUBARU. Before the installation, we confirmed basic performances such as the beam current sensitivity of 1.24 V/A, wide frequency response of up to 100 MHz, etc. The beam test was performed at the new linac of NewSUBARU and beam charge measurement performance, common-mode noise cancellation, etc. were evaluated. The differential CTs have been utilized for stable beam charge monitoring in the NewSUBARU linac.

INTRODUCTION

Reliable monitoring of the charge and current of a particle beam is important for most particle accelerators. A current transformer (CT) is often used as a non-invasive beam charge and current monitor. The signal output of a CT is usually designed as a single-ended coaxial line. If a single-ended CT is located near a pulsed high-power component, a common-mode noise can be overlapped with a beam signal and the noise can deteriorate the measurement accuracy.

To mitigate the noise from the high-power component, a differential CT was proposed and utilized in the X-ray free-electron laser, SACLA [1, 2]. This differential CT has four single-turn coils around a toroidal magnetic core, where two coils generate positive signals and the other two generate negative signals. A common-mode noise can be canceled out by subtracting the positive and negative signals. Since each signal output is a single-ended coaxial line, however, a preamplifier or a balun near the differential CT is required to transform two differential single-ended signals into a balanced differential line for long signal transmission.

A new 3 GeV light source project, NanoTerasu [3, 4], was proposed and it is now being constructed in Sendai, Japan. Before the construction of NanoTerasu, a new injector linac for the NewSUBARU storage ring [5] was constructed as a prototype of the NanoTerasu linac [6]. One of the most important design concepts of these accelerators was low-cost and easy maintainability. A differential CT should also be low-cost and the number of components in the system should be as small as possible. Therefore, we designed a new differential CT that did not need a preamplifier near the CT.

DESIGN

A new differential CT aims to extract a balanced differential signal directly from a coil. Therefore, we designed a CT having two-turn pickup coils wound on a toroidal magnetic core and the midpoint of each coil is grounded. A schematic view of the new differential CT is shown in Fig. 1. Four pickup coils are attached to a toroidal core at equal intervals (90 degrees) and a beam pipe with a ceramics gap is inserted into the core. The toroidal core is Finemet FT-3KM F7555G supplied from Hitachi Metals, which has enough permeability as high frequency as 1 GHz. An 11 Ω resistor is attached to each coil in parallel to attenuate a beam signal. The signals from pickup coils are extracted from four LEMO 0S302 series 2-pin connectors. A photograph of the differential CT is shown in Fig. 2. The four balanced differential signals are transmitted to a readout electronics by a Category-6 (CAT6) S/FTP cable for Ethernet, which has good high-speed signal transmission characteristics and a reasonable price.

The beam current sensitivity of each turn of the pickup coil is 0.125 A/A since the number of total turns is 8. The voltage sensitivity of the output to the beam would be 12.5 V/A without any parallel resistors since the characteristic impedance of the balanced differential line is 100 Ω. Since the sensitivity of around 1 V/A is easy to deal with for us, an 11 Ω metal-film resistor (±0.1 % accuracy) is inserted in parallel with the pickup coil to attenuate the signal amplitude. The sensitivity is reduced by a factor of 0.099 and the current and voltage sensitivity are finally decreased to 0.0124 A/A and 1.24 V/A, respectively, which corresponds to –35 dB relative to the beam current.

The readout electronics consists of an amplifier unit and a high-speed digitizer. The block diagram of the amplifier unit is shown in Fig. 3. The S/FTP cable from a differential CT is received by an M12 X-coded connector, which is more reliable than an RJ-45 modular connector. Common-

† maesaka@spring8.or.jp

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mode noise in each balanced differential signal is suppressed by a common-mode choke filter and a high-frequency component is blocked by a low-pass filter having a cutoff frequency of 10 MHz. The filtered differential signal is converted to single-ended by a differential amplifier. The four signals are then summed and outputted from SMA connectors. The signal from the amplifier unit is recorded by a high-speed digitizer, such as SIS8325 [7] (250 MSPS, 16 bits).

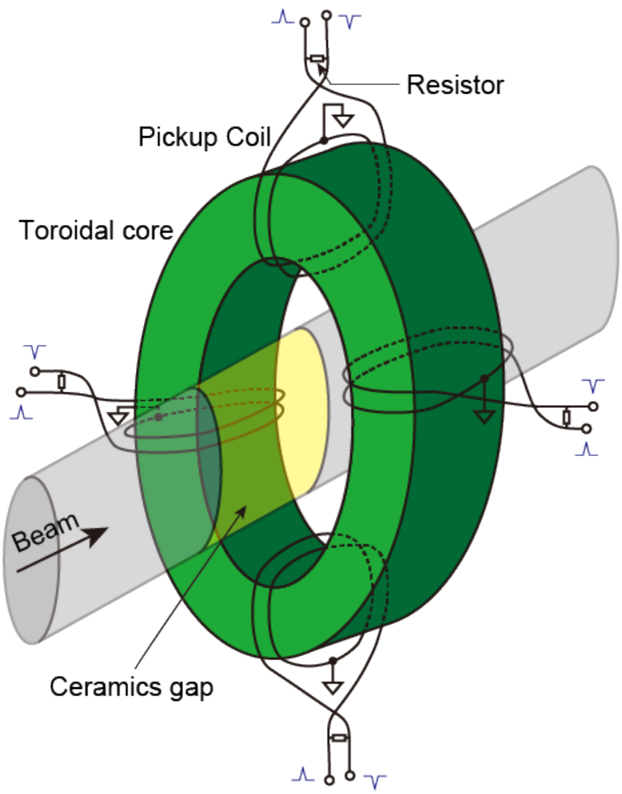

Figure 1: Schematic view of the differential CT.

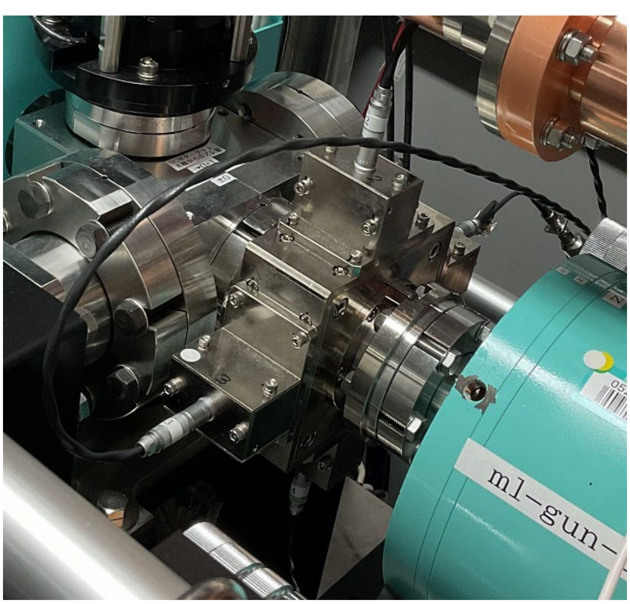

Figure 2: Photograph of a differential CT installed in the new injector linac of NewSUBARU.

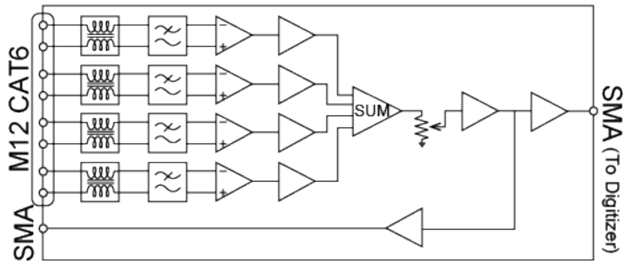

Figure 3: Block diagram of the amplifier unit.

LABORATORY TEST RESULTS

We produced differential CTs for the new linac for NewSUBARU and evaluated electrical response before installation. A schematic view of the response measurement setup is shown in Fig. 4. An electron beam was simulated by a rod in the beam pipe and two taper lines were connected to both ends of the pipe to adapt the 50 Ω coaxial transmission line smoothly.

The frequency response was measured by a 4-port vector network analyzer (VNA). Two ports are connected to both ends of the taper lines and the other two were connected to one of the four differential outputs (one port for the positive pin and the other for the negative). The unused three outputs were terminated by 100 Ω resistors. The frequency response from the beam port to the normal mode of each output is plotted in Fig. 5. The responses of the four outputs were almost flat and identical up to 100 MHz. The insertion loss was –36 dB in the low-frequency region, which was consistent with the design value. The frequency response to the common mode is plotted in Fig. 6. The signal from the beam to the common mode is suppressed by approximately 30 dB compared to the normal mode up to 10 MHz.

The pulse response was also tested by using a fast pulse generator. A rectangular pulse of 5 V height and 1 ns width was applied to the beam port, corresponding to a 100 mA beam current and a 100 pC beam charge. The output waveforms are shown in Fig. 7. The peak voltage is 0.08 V, which is –36 dB of 5 V. The pulse width is 1.4 ns FWHM, which is fast enough for our application.

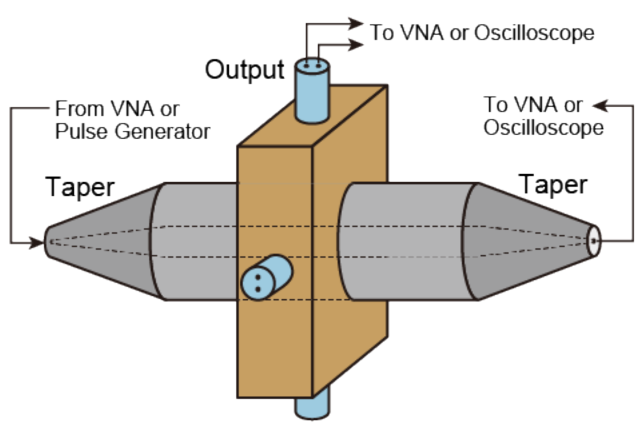

Figure 4: Schematic view of the response measurement setup.

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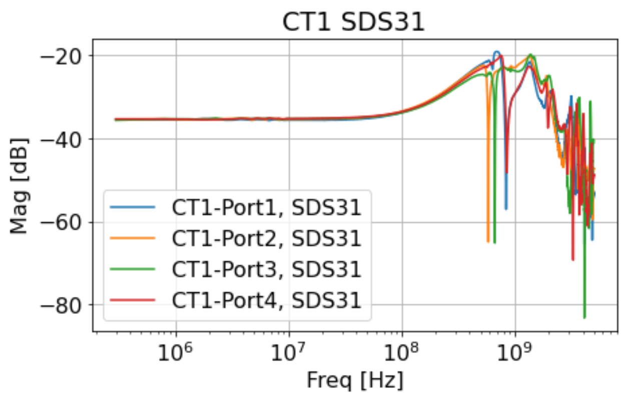

Figure 5: Frequency response of the transmission coefficient from the beam port to the normal mode of each output channel.

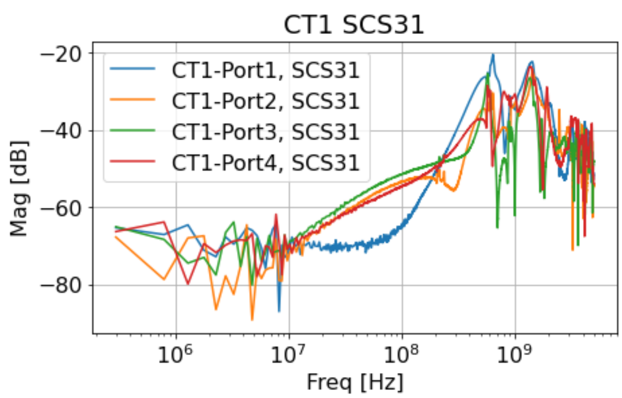

Figure 6: Frequency response from the beam port to the common mode of each output channel.

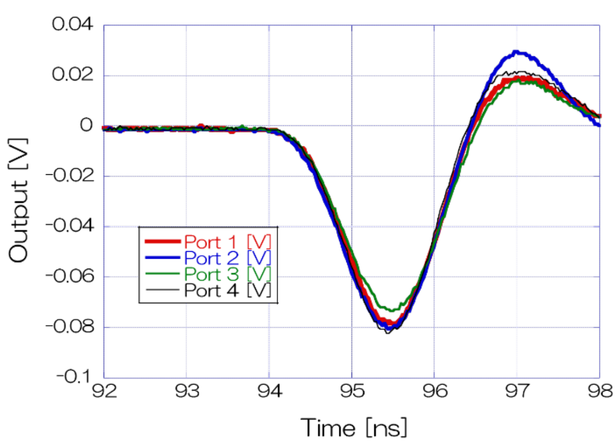

Figure 7: Output waveforms from a rectangular pulse of 5 V height and 1 ns width.

BEAM TEST RESULTS

After the construction of the new linac for NewSUBARU, we tested the differential CT with an actual electron beam. A signal waveform from a differential CT is shown in Fig. 8. The beam charge was approximately 1 nC in this case and the signal was taken by an oscilloscope with a coaxial cable of approximately 20 m-long. A short pulse width of less than 1 ns FWHM was observed, which was fast enough for our application. The pedestal level was not affected by common-mode noise from high-power components near the CT. When a single pin of the CT was observed, the fluctuation of the ground level was significantly larger than the balanced differential signal. Thus, the noise tolerance of the differential CT was confirmed to be sufficient.

Figure 9 shows a waveform taken by a SIS8325 MTCA.4 digitizer after an amplifier unit. The beam charge of this waveform was approximately 0.5 nC. The pulse width was stretched to about 20 ns FWHM by a low-pass filter in the amplifier unit. The peak value is used for calculating the beam charge. The beam charge data have been stably recorded to the database system of NewSUBARU and utilized for the stable operation of the injector linac.

Figure 10 shows a waveform when one wire in the CAT6 differential cable was accidentally disconnected. The ground level is heavily disturbed by common-mode noise from a high-power pulse component. The noise level is comparable to the beam signal and it is difficult to monitor the beam charge precisely. Since the disconnected floating wire can be an antenna to receive the noise, the observed noise is somewhat enhanced. However, a conventional single-ended CT is thought to be affected by this noise to some extent. Thus, the noise suppression capability of the differential CT is important for precise beam charge monitoring in a noisy environment.

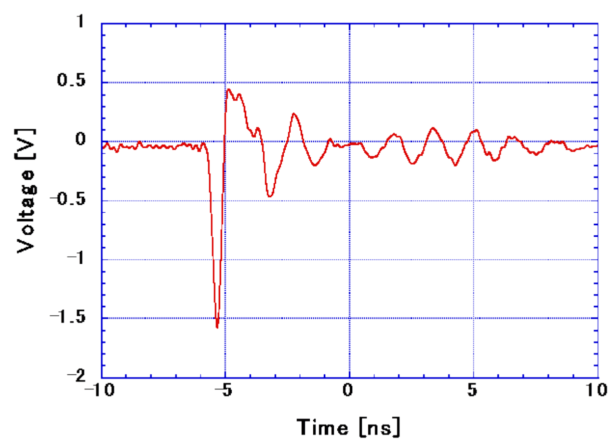

Figure 8: Beam signal waveform of a differential CT.

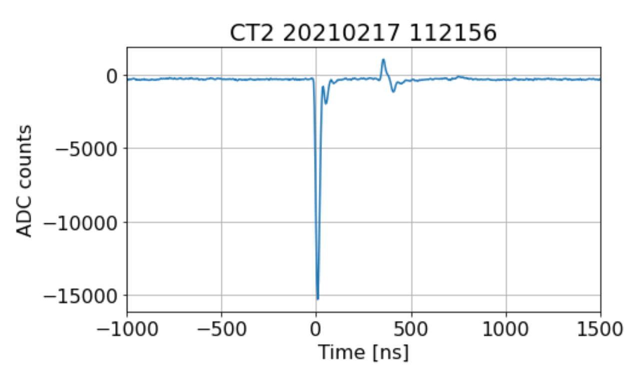

Figure 9: Beam signal waveform taken by an MTCA.4 digitizer. The sampling rate is 238 MHz and the ADC full scale is ±32767.

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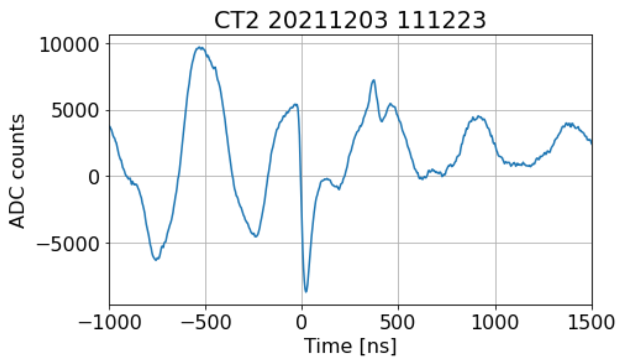

Figure 10: Abnormal waveform when one wire of the CAT6 cable was disconnected.

SUMMARY

We designed a new low-cost differential CT to monitor the current and charge of an electron beam without common-mode noise from high-power components. This differential CT was installed into the new injector linac of NewSUBARU and will be used in the linac of NanoTerasu. This differential CT has a toroidal magnetic core with four two-turn pickup coils and the midpoint of each coil is grounded to generate a balanced differential signal. A readout electronics consisting of an amplifier unit and an MTCA.4 high-speed digitizer was also developed. Electrical characteristics of the differential CT, such as frequency response and pulse response, were evaluated in a laboratory and the results were consistent with the design. The beam current sensitivity was 1.24 V/A and the frequency response was sufficiently flat up to 100 MHz. The differential CT was tested with an actual electron beam during the beam commissioning of the new linac for NewSUBARU. Appropriate waveforms of electron beams were observed as expected and the CT data have been utilized for stable operation of NewSUBARU.

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