DUAL-MODE BEAM CURRENT MONITOR

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Abstract

We developed beam-current transformer (CT) appropriate for monitoring beam of an accelerator having operating period of less than a few seconds. The monitor has two operating modes. The CT at the fast mode, having frequency rage of a several Hz to 1MHz, enables an accurate observation of beam at injection process. The CT at slow mode displays the circulating beam current and the particle number. In order to make installation easy, the core of CT is divided into two pieces. The number of coil windings is only 55 turns for half piece of core. This makes easy to manufacture the CT and also enables the operation of the CT in fast-mode. To lower the cut-off frequency at slow mode operation, we employed the negative impedance circuit, this also makes manufacture easy.

The accelerator at the Wakasa-Wan Energy Research Center (WERC) installed by HITACHI-Ltd [1] has a fast CT having the bandwidth of 400Hz to 7MHz and electro-static charge monitor for bunched beam. Accurate observation of the extraction process is not possible by the system. Thus this monitor is developed for the accelerator at WERC.

PRINCIPLE

The circulating beam passing through the toroidal core of CT is considered to be the primary winding. The secondary winding on the core is the pick-up coil. The lower cut-off frequency (ω_L) of the CT is given by the resistance (R) of termination resistor including that of pick-up coil, and its inductance (L); $\omega_L = R/L$. In order to minimize R, HEREWARD transformer uses the low input impedance characteristic of an operational amplifier [2]. In this case, however, R, i.e. ω_L, remains a finite value. A feedback technique, which cancels the flux in the core via the other feedback winding, can also decrease ω_L. This type of CT is used at KEK-PS [3]. In this case, the number of winding of the pick-up coil amounts to 1000 turns to obtain sufficiently low cut off frequency.

In our case, Negative Impedance Circuit (NIC) is employed to obtain a perfect cancellation of the resistance R. Figure 1 shows circuit diagram of the CT at slow mode. In the figure, I_B represents the beam current, and L, R_0 represent the inductance and the resistance of pick-up coil. The input impedance (Z_{IN}) at the inverting-input of the operational amplifier is given by
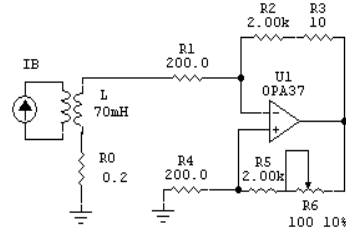
$$Z_{IN} = -R_4 \cdot \frac{R_2 + R_3}{R_5 + R_6}.$$

Figure 1: The circuit diagram of the CT using NIC.

The input impedance is negative and, by adjusting the value of R_6, the impedance Z_{IN} can be made to be $-(R_0 + R_1)$. At this condition, the system has a response even for DC component of I_B. The output voltage is given by

$$V_{OUT}(\omega) = \frac{I_B(\omega)}{n} \cdot (R_2 + R_3) \cdot \left(1 + \frac{R_4}{R_5 + R_6}\right)$$

$$\cong \frac{I_B(\omega)}{n} \cdot (R_2 + R_3),$$

where n is the number of turns of the pickup coil. In this case n = 110. Therefore the system in the Figure 1 has a response of $V_{OUT}/I_B = 20$V/A. Since typical beam current of the machine changes from 50mA at injection to 200mA at flat-top, output voltage varies from 1V to 4V. Nearly 6V headroom at output voltage of the amplifier is kept for future improvements of the accelerator.

While the system has a response of DC-component, its absolute value is not definite. Therefore we must artificially set the output to zero when I_B is zero. The drift of offset voltage of the amplifier also limits the operating time of the CT. Therefore this CT is adequate for the rapid cycle accelerators.

At fast CT-mode, the pick-up coil is switched to the inverting-input of an operational amplifier having a fast response. That is, CT is used as traditional HEREWARD transformer.

PRACTICAL SYSTEM

The FINEMET (FT–3M by Hitachi-metal Co.) is used for the magnetic core of CT. FT-3M is used because of its large permeability which makes the inductance of the pick-up coil large. The large inductance makes the adjustment of the time-constant easy and reduces its drift due to the finite temperature coefficient of the coil

resistance. The outer diameter of core is 215 mm; inner is 158 mm, and 25 mm-thick. The core is divided into two pieces as shown in Figure 2. The inductance of the pick up coil of 110 turns is nearly 60 mH.

Figure 2: Photo of the core divided into two pieces.

Since the circuit shown in Figure 1 was not stable, we had to damp the oscillation with connecting 4nF feedback capacitor. Simplified circuit diagram of the front-end amplifier is shown in Fig. 3. This capacitor increases the rise-time for the step signal to 200 μsec. In order to drive coaxial cable, an inverting amplifier with current buffer must be connected.
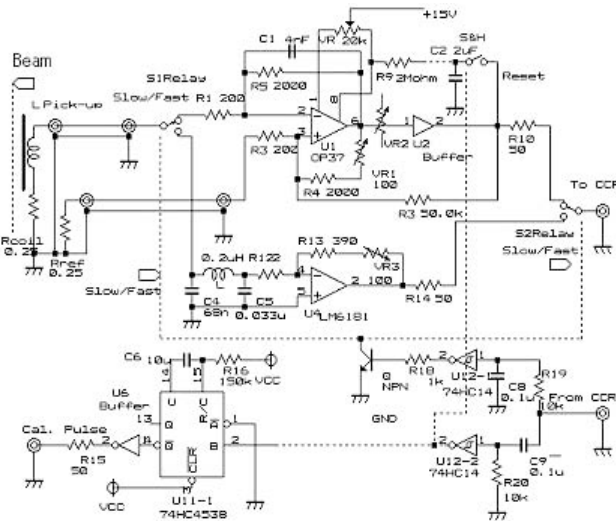

Figure 3: Simplified circuit diagram of the front-end amplifier module.

In order to stabilize time constant, reference copper-wire resistor, having nearly the same resistance as that of the pick-up coil, is put near the core, and the resistor is connected between R_3 and ground. The feedback from the output to positive input of the amplifier of NIC with 50kΩ stabilizes the offset voltage. In order to stabilize further the offset voltage, output voltage sampled when the beam current is zero. The sampled voltage is fed back to NIC-

operational amplifier; the resistor of 2MΩ is connected from the sample hold circuit to pin-8 of the amplifier.

The result of the test operation of the slow CT mode is shown in Fig. 4.

Figure 4: Upper trace is test signal with amplitude of 53mA, and the lower is the output signal having amplitude of 1.06V. The width of pulse is 0.89sec.

The response to a burst pulse with frequency of 500 kHz and 6 MHz is also tested. The duration of the burst is 1sec. At an early stage, we observed a frequency dependence of the time constant. This effect was due to an RF noise onto the circuit.

The circuit is switched with reed relay to fast CT mode. The reed relay is selected because of its stability of the contact resistance. In order to eliminate the abnormal response due to a parasitic resonance of the pick-up coil at a several-MHz, a low-pass filter with the cut-off frequency of 1 MHz is installed in front of the amplifier. While the response of the system is limited to only 1MHz, this is sufficient to observe the beam at injection process. The low-frequency cut-off is selected so as to make an error of less than 5% at 200 μsec of pulse duration. In order to obtain a better step response we selected the Gaussian-type filter. Gain of the fast mode CT is set at 1 V/500 mA at 50 Ω-termination. This gain is obtained by adjusting the value of R_{13} +VR_3 to 440Ω.

The signal flow diagram of the system is depicted in Fig. 5. Signal is transmitted via coaxial cable with a length of 100m to the Center Control Room (CCR). The receiver amplifier has the function, which restores again the output to zero at $I_B = 0$. The output of this amplifier is proportional to the circulating beam current, and its amplitude is 1V at 50mA beam current. The circulating beam current is also connected to the normalization circuit, which divides the current by the accelerating frequency and produces the signal indicating the number of accelerating particles. The gain of this output is adjusted to 1V at 5×10^{10}ppp.
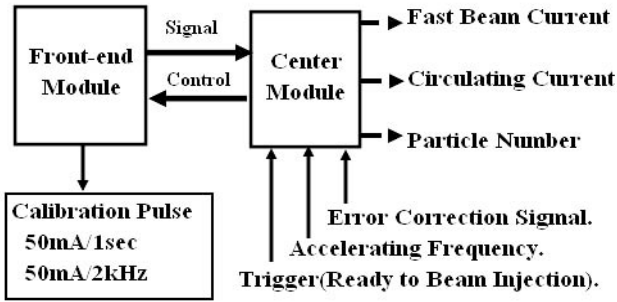
Figure 5: The signal flow diagram of the system.

The receiver amplifier has an input terminal of the correction signal. This signal corrects the error due to the leak field which will be described at the next section.

At the CCR, the system produces the pulse which is synchronous to the end of the accelerator cycle, or timing pulse of "ready to beam injection". The pulse is stretched to the width of 150μsec, and transmitted to the front-end amplifier module with coaxial cable. The level signal, with which we can switch the slow CT-mode to fast mode, is superposed onto the same coaxial cable.

The expected characteristics of the monitor are listed in Table 1.

Table 1: Expected characteristics of the CT. The mark (*) indicates that signal is measured with 50Ω-termination.

	Sensitivity (Error)
Slow CT Mode	1V/50mA (±5%)
Particle Number	1V/5·10^{10}ppp. (±5%)
(Frequency range)	~DC to 6kHz
Fast CT Mode	1V/500mA (±5%)*
(Frequency range)	~1Hz to 1MHz

MAGNETIC FIELD SHIELDING

Since the core is installed at nearly 25cm downstream position of the bending magnet, the leakage magnetic field at the core amounts to a few kG. Since the permeability of the core is $1×10^5$, the leakage field is large enough to saturate the core. Thus the shielding of the field had to be designed. At the first step we used POISSON to design the shield. Secondly, three dimensional calculation of the field using OPERA is performed to check the results of POISSON. Figure 6 shows the design of the shielding box and result of the calculation, where the magnet flux density in the core is also shown.

The maximum magnetic flux density in the core can be reduced to less than 300 gauss that is less than the saturation-level. The flux density in the core is due to open windows at the two sides.

The field produces an error signal with amplitude which is comparable to the beam signal. We are studying the technique of the compensation for the error due to the leakage field. The output signal of the monitor is recorded during no beam acceleration, and the recorded signal is superposed to the receiver amplifier with inverting its polarity. Thus the error can be reduced. A transient recorder, using an IC used for a voice recorder, is under development.
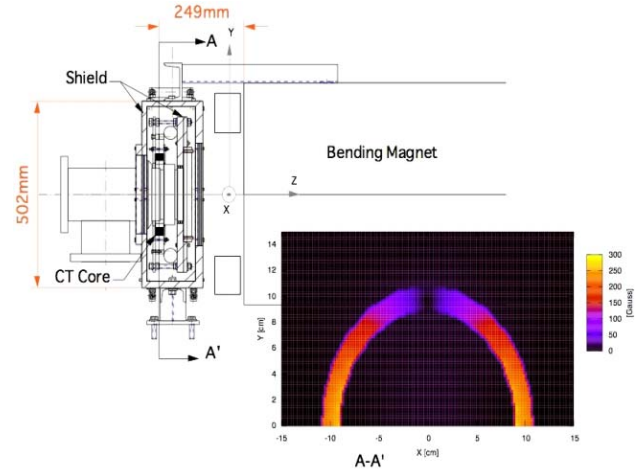

Figure 6: Design of the shielding box. Color- graph on the right shows the field in the core.

DISCUSSIONS

The system is only operating at the laboratory at KEK. Therefore error correction and the stability are not tested under a real operating condition. Therefore (1) we must reinforce the shield against the leakage magnetic field from the bending magnet, and (2) the study on the reduction of the noise from the leakage field is necessary for a real use.

The stability of contact resistance of the relay used for the mode switch is effective to the time constant of slow mode. If the resistance is not stable as expected for long period operation, the dual-mode operation becomes not possible. For this situation, we are planning to improve the fast CT installed by HITACHI. Lower cut-off frequency of the CT can easily be reduced from 400Hz to a several-Hz, if the output of the CT is connected to the amplifier used for the fast mode (see Fig. 3.). In this case, we must remove the word, "DUAL-MODE", from the title.

ACKNOWLEDGEMENTS

REFERENCES

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