DEVELOPMENT OF HIGH-SPEED DIFFERENTIAL CURRENT-TRANSFORMER MONITOR

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Abstract

A new current-transformer (CT) monitor for the XFEL/SPring-8, called “SACLA”, was developed. In the SACLA, the bunch length of an electron beam is compressed from 1 ns to 30 fs, and the beam charge decreases to obtain a genuine electron beam from 1 nC to 0.3 nC along with acceleration. Tis new CT monitor must be able to measure the charge of the electron beam and monitor bunch length in velocity bunching. To satisfy this requirement, the CT has two advantageous properties. One is a differential output signal that suppresses common-mode noise from the thyratron of a klystron modulator by a factor of ten. The other property is a high-speed signal output that makes it possible to measure the bunch length and time-of-flight at the injector part of the SACLA. The output signal has 200 ps rise-time and a pulse width of 400 ps (FWHM) for an impulse beam. Bunch length between 1 ns and 400 ps was measured around a 238 MHz buncher cavity. Moreover, the TOF of a low energy beam between two CTs was measured with a few picoseconds resolution. It was thus confirmed, the performance of the new CT is sufficient for the SACLA.

INTRODUCTION

The x-ray free-electron laser (XFEL), named “SACLA” (SPring-8 Angstrom Compact Free Electron Laser), was constructed in the SPring-8 site [1, 2]. The SACLA succeeded in XFEL lasing with a wavelength of 0.12 nm [2]. For the sake of precise measurement of beam charge at SACLA, a new differential current transformer (CT) was developed [3-5] and employed. The new CT is required to measure two quantities: electron charge and bunch length of an electron beam.

In regard to the SACLA, the electron charge decreases from 1 nC to 0.3 nC along the accelerator so as to achieve a genuine electron beam for lasing. The electron charge and beam transmission efficiency are monitored by CT monitors. However, it is difficult to specifically measure signals of some monitors, since there is considerable noise from the thyratrons of a klystron modulator [3]. To measure the electron charge, CT monitors are required to reduce the environment noise.

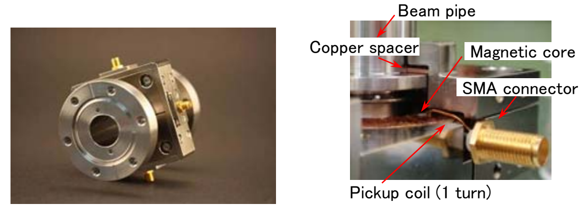
In addition, to achieve the peak current of 3 kA, the bunch length is compressed from 1 ns to about 30 fs through velocity bunching process in the injector [6] and magnetic bunching process in three bunch compressors by using a four-bending-magnets chicane. To obtain stable lasing, it is necessary to monitor bunch length and beam energy in these bunching processes with non-destructive feature. Therefore, the CT must have sub-nanosecond response for a low-energy beam around 1 MeV in the injector part.

In this paper, we describe the properties of the CT confirmed by using an electron beam from the SACLA.

OVERVIEW OF HIGH-SPEED DIFFERENTIAL CT

The configuration and the inner structure of the CT are shown in Fig. 1.

A beam duct insulated with a ceramic ring is employed as the vacuum beam duct for the CT. A finemet core (Hitachi Metal, Ltd.) [7], which is capable of observation in a high frequency region, is placed on the outer side of the ceramic ring. Four pickup coils with SMA output connectors are one turned around the finemet core, which have a short lead with 40 mm long in order to obtain a fast signal. One pair of coils is arranged along the horizontal axis, and the other pair is arranged along the vertical axis. Consequently, the output signals of one pair are a positive signal and a negative one, respectively. Subtracting the negative signal from the positive one in the pair, thus removes any common-mode noise. Moreover, the beam-position dependence is eliminated by averaging the signals from all four output ports. The CT



(a) (b)

Figure 1: (a) Photograph of a high-speed differential CT monitor and (b) the inner structure.

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was assembled using a copper spacer between an aluminium CT's case and the beam duct so as to obtain good electric connection. The ground of the SMA output connectors was connected to the CT's case. The CT was attained to generate fast output signal by the structure.

The output signals are amplified by using a two-stage amplifier, which integrates the output signal pulse to monitor electron charge. The amplified signal is recorded by VME A/D converters with a 238 MHz sampling rate. The raw signals from two CTs, that are installed in the most upstream of the SACLA, and are also monitored directly with a high-speed oscilloscope for low-energy beam properties.

PERFORMANCE OF HIGH-SPEED DIFFERENTIAL CT

The basic performance of the high-speed differential CT was evaluated. Preliminary performance of the CT had been reported in Refs. 3-5. This performance was obtained by using an electron beam of the SCSS test accelerator which was constructed before the SACLA.

It was confirmed that the differential CT \reduces common-mode noise from environmental noise by a factor of ten through subtracting the one pair signals. These signals are shown in Fig. 2. As a result, a dark current of about 1 pC from a C-band accelerator was also measured by the differential CT in the SACLA. The CT was confirmed that the output signal of the CT is a linear response to the electron charge. The obtained response output is shown in Fig. 3. Accordingly, these performance results show that the CT can be utilized for monitoring the electron charge and transport of the electron beam in the SACLA.

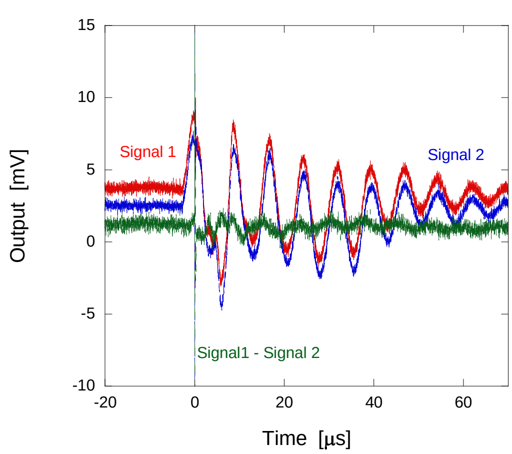

Figure 2: Output signals of the differential CT with environmental noise. The signal 1 (red line) and signal 2 (blue line) are raw data from the CT. The signal 1 is positive output and the signal 2 is negative one. The green line is a subtracted signal from signal 1 to signal 2.

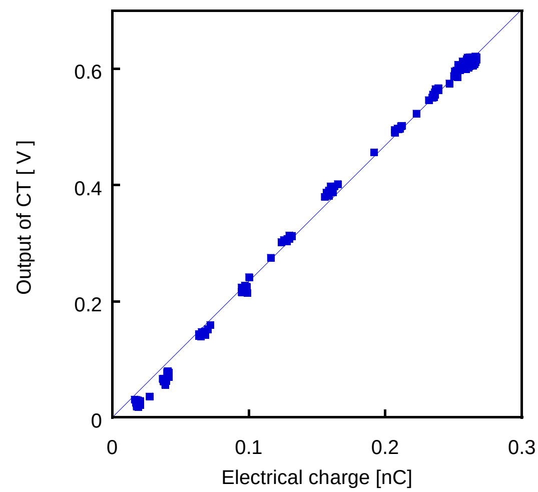

Figure 3: Output response of the CT versus the electron charge for the electron beam of the SCSS test.

For another purpose, namely, monitoring the bunch length around the injector part of the SACLA, the CT must have a high-speed response. The response speed was evaluated by using the electron beam after the 238 MHz sub-harmonic buncher (SHB) for the injector part of the SACLA. The setup of the injector part, which has acceleration cavities and two CTs, is shown in Fig. 4. The electron beam from a thermionic gun is cut down to a bunch length of about 1 ns by a beam chopper. The bunch length is then compressed by velocity bunching through the buncher cavities.

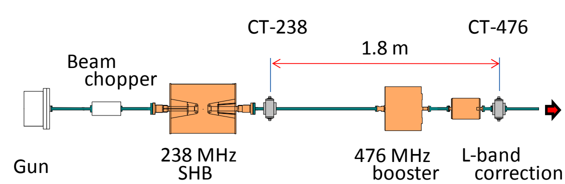

Figure 4: Layout of the injector part in the SACLA.

The pulse width of the output signal from the CT-476 was measured when the RF-power of the 238 MHz SHB was changed. The results are shown in Fig. 5, and the peak value of the CT-476 output signal is plotted in the same graph. The pulse duration of the output signal decreases with increasing the RF-power of the 238 MHz SHB, indicating that the bunch length is decreased by the velocity bunching. Around 400 ps, the pulse duration of the CT is saturated in spite of changing the RF-power. The pulse duration of 400 ps is thus considered the limited response of the CT, which is consistent with the result from the SCSS [3]. The shortest output signal is 400 ps and rise time is 200 ps (10-90%).

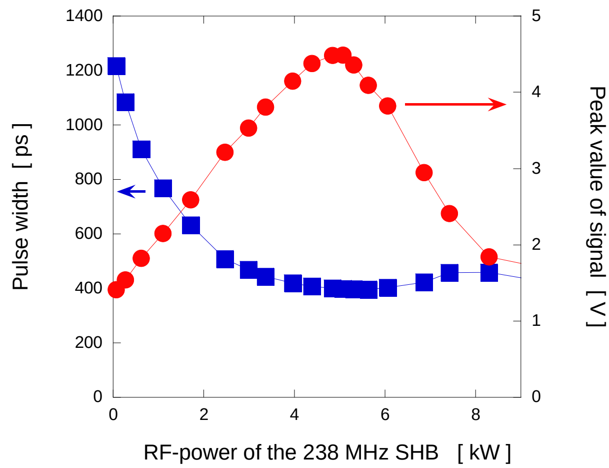

Figure 5: Output response of CT -476 versus RF-power of the 238 MHz SHB. One is the pulse duration (FWHM), and the other is the peak value of the output signal from the CT.

In Figure 5, the pulse duration of the CT-476 is saturated when the RF-power is more than 3 kW. The peak value of the CT signal increases, however, until the RF-power becomes 5 kW. To monitor the peak value of the signal, it is possible to observe change of the bunch length below 500 ps.

At the same time, the CT has the other purpose, namely, monitoring electron charge. When the peak value was increased, the electron charge, which is measured by integrated output signal from the CT, was constant. When the RF-power exceeded 5 kW, the peak value and integrated value also decreased. It is conceivable that the electron beam was over bunching and lost the electron charge before the CT-476 for the RF-power range. On the whole, the CT has the capability of monitoring a change of the bunch length and peak current around the injector part.

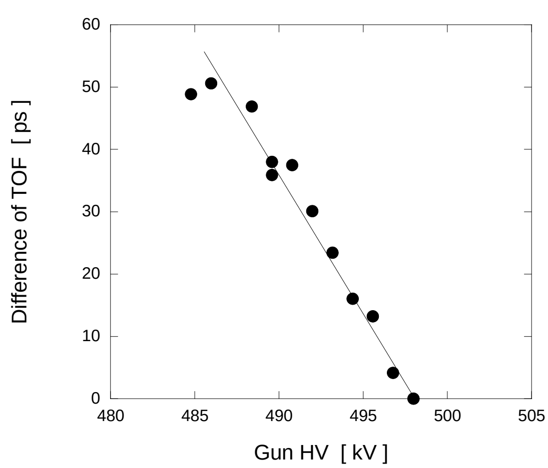

Figure 6: Difference of time-of-flight (TOF) measured by CTs in the injector part of the SACLA. TOF is plotted under the assuming that TOF is zero at gun HV of 498 kV.

Moreover, it is possible to measure time-of-flight (TOF) by using two CTs around the same the low energy region. TOF is obtained from the time difference between the rising edges of CT-238 and CT-476. Measured TOF under varied acceleration voltage of the electron gun is shown in Fig. 6. It is clear that the TOF decreases when the velocity of the electron beam is increased by intensifying the voltage.

These results indicate that the CT can monitor electron charge and bunch length around sub-nanosecond region and TOF for the injector part.

CONCLUSIONS

A new CT monitor for SACLA has been developed and constructed. The CT has four output ports, which compose provide two differential signals, and can reduce the environmental noise from klystron noise down to 1/10. By virtue of this noise improvement, the CT is possible to monitor electron charge in a range from 1 pC to 1 nC. Furthermore, it has a fast temporal response; that is, the rise time and the shortest pulse width are 200 ps and 400 ps, respectively. Thanks to these properties, the CT can monitor the bunch length and TOF of a low-energy beam of around 1 MeV. These results confirm that the performance of the new CT is sufficient for the SACLA. In the SACLA, 30 of these high-speed differential CTs have been installed along the accelerator.

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