THE NEW BEAM CURRENT TRANSFORMER FOR IR-FEL FACILITY AT NSRL*

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Abstract

The beam current transformer (CT) is an important part of the beam diagnostics system as a kind of non-destructive intensity measurement. The beam CT has the strong dependence of the sensitivity and time constant on the time structure of the beam. To measure the macro-pulse beam intensity with 5-10μs length and 238 MHz micro pulse repetition rate in the IR-FEL facility [1]. It is necessary to find a suitable material as the CT core which can meet the measure requirement of the beam current. In this paper, we figured out the key factor of the suitable material to be the CT core and three different magnetic materials were tested to find out that the laminated Fe-based nanocrystalline alloy core owned the best performance. Then, we designed the mechanical structure and improved the test device. The finished products have passed the acceptance test.

INTRODUCTION

The Infrared Free Electron Laser (IR-FEL) facility is currently under construction, which provides electron energy from 15 to 60 MeV, beam bunch with a macro-pulse length of 5-10 μs and a general micro-pulse repetition rate of 238 MHz. The beam current will be a first check concerns in the future daily operation. So it is important to develop a reliable beam current transformer which can meet the requirement to measure intensity and time structure of the bunch. The CT is non-intercepting, whose basic principle is the detection of the magnetic field carried by the beam. In the beam detection positon of the vacuum chamber, there will be a ceramic slit, and an outer ring with high magnetic permeability. Then an N-turn coil on the magnetic ring will pick up the electricity signal. A shielding box will stop the wall current to make sure that only the beam current pass through the beam current transformer. Figure 1 shows the schematic of the beam current transformer. The inductance of the magnetic ring is determined by

$$L = 2N^2 \mu_i h \ln(\Phi_{out} / \Phi_{in}) \times 10^{-10} \quad (H) \qquad (1)$$

where μ_i is the initial permeability, and Φ_{out}, Φ_{in} and h are the outside diameter, insider diameter and thickness of the ring respectively. The inductance is the key parameter which determines the performance of the beam current transformer. So we should put focus on the permeability and its geometrical size of the magnetic ring.

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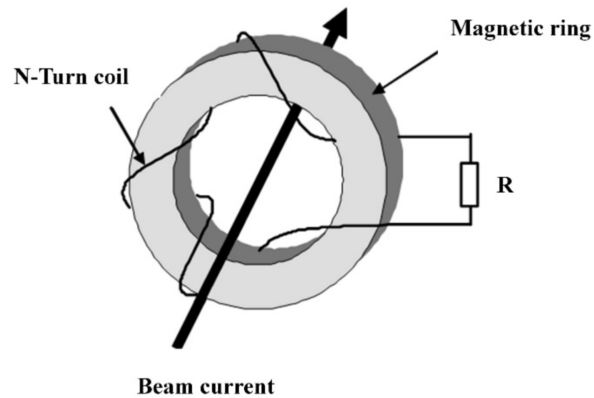

Figure 1: Beam current transformer schematic.

THE MAGNETIC CORE

As we know, it is hardly to meet the requirement to measure both long pulse and short pulse at one CT. For the long pulse, the signal of the induced voltage is exponentially decayed with the time constant $\tau = L/R$. So the magnetic core with higher initial permeability and more coil can increase the time constant and reduce the droop of the induced signal. But for the short pulse, the induced voltage signal is exponentially rose with the time constant $\tau = L_2 /(R+R_C+R_2)$, in which L_2 is the leakage inductance, R_C is the loss resistance of the magnetic ring, and R_2 is the resistance of the coil. We need to reduce the turn number of the coil to decrease L_2, so that the rise time will be shorter, which is. However, contrary to measuring long pulse. So we should find a suitable material with higher initial permeability and less iron loss, to reduce the lower limit of the pulse length by decreasing the coil turns. Meanwhile, the good performance of long pulse measurement can be kept.

MATERIAL PERFORMANCE

There are three categories of the common magnetic ring material: nanocrystalline, ferrite and silicon. After investigation, we selected the Fe-based amorphous magnetic ring as the CT core. Because of the irregular arrangement of atomic atoms in the material, exhibits many excellent electromagnetism and chemical properties such as high strength and toughness, corrosion resistance, high resistivity, high saturation of magnetic induction, high permeability, low loss and so on [2]. Table 1 shows part of the performance comparison between FeSiB and ferrite.

Table 1: Performance Comparison Between FeSiB and Ferrite

Parameters	FeSiB	Ferrite
Saturation magnetic induction (T)	1.25	0.5
Remnant magnetization (T)	<0.20	0.2
Iron loss (20KHz/0.2T) (W·Kg)	<3.4	7.5
Magnetic permeability (Gs/Oe)	>50000	2300
Curie point (°C)	570	<200

MAGNETIC RING TEST

We tested three different Fe-based nanocrystalline magnetic ring to pick the best one as the CT core. These three magnetic rings (with the serial number a, b and c) have the same material but are different in workmanship and geometrical size, see Figure 3. The test system is shown in Figure 2.

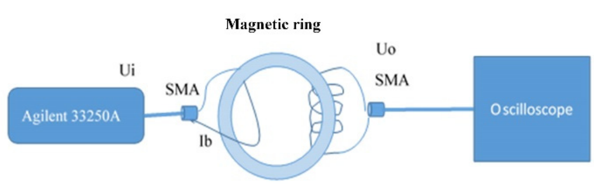

Figure 2: Block diagram of the magnetic ring test system.

The input signal is generated by Agilent 33250A signal source with a repetition frequency of 100 Hz and a pulse width of 5μs, 8 μs, 10 μs and 12μs, respectively. The output signal voltages are from 2 V to 10 V. An oscilloscope will observe the waveform and record the signal data. The input coil is signal turn, while the output coil is 10 turns [3]. After dealing with the signal data, we calculated out the sensitive S and the droop D of each ring. The sensitive of each ring is $S_a = 4.754$, $S_b = 4.84$, and $S_c = 4.89$, with a droop of $D_a < 1.65$ %/μs, $D_b < 1.10$ %/μs and $D_c < 1.0$ %/μs, respectively. The third magnetic ring has the best sensitivity and the least droop. So we chose the third magnetic ring as the material of the CT core.

(a) (b) (c)

Figure 3: Pictures of three magnetic ring.

CT PERFORMANCE TEST

Figure 4 is the picture of new CT. We keep a test signal input port, which makes the test more convenient. We test several CTs, and we choose one as the representative to show the test result.

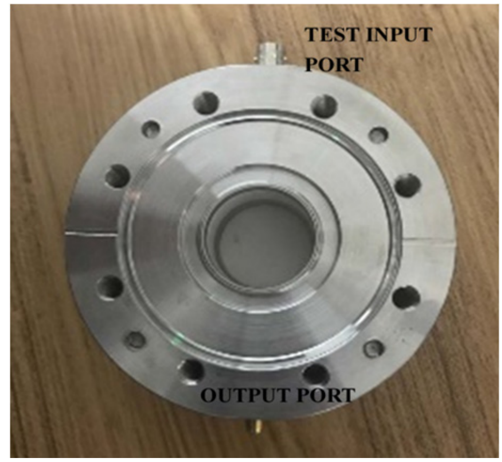

Figure 4: Picture of the beam current transformer.

LONG PULSE MEASUREMENT

The long pulse signal is generated by Agilent 33250A signal source with a repetition frequency of 10 kHz and a pulse width of 5 μs, 8 μs, 10μs and 12μs, respectively. And the signal voltages are from 1 V to 5 V. The waveform of the output signal was observed and recorded by oscilloscope. Figure 5 gives the waveform of a long pulse with10 μs width.

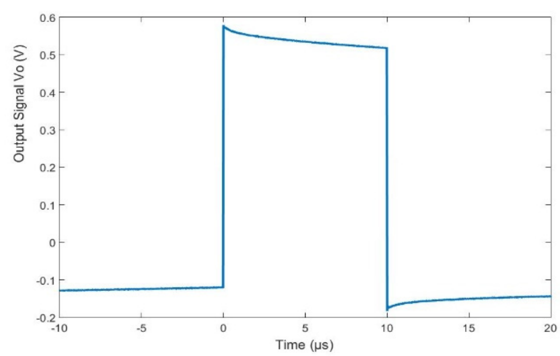

Figure 5: Waveform of a 10 μs pulse.

Then we calculated the sensitivity and droop in every situation, and plotted the curves of them with voltage at different pulse widths. The sensitivities obtained by linear fitting at different pulse widths, Figure 6 shows the fitted lines, and Table 2 shows the fitted expressions and the sensitivity values.

Table 2: Sensitivity Values with Different Pulse Width

Pulse width	Fitting expression	S
5 μs	$Vo = 0.1718Vi+2.05\times10^{-3}$	4.296
8 μs	$Vo = 0.1706Vi+5.18\times10^{-3}$	4.265
10 μs	$Vo = 0.1725Vi+1.65\times10^{-3}$	4.312
12 μs	$Vo = 0.17235Vi+2.41\times10^{-3}$	4.309

According to the result, the sensitivities S are well consistent. The reference value is 4.30, the standard deviations is about 1.53%. The droop we measured are

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always under 1.5 %/µs, see Figure 7, which satisfies the target of long pulse measurement.

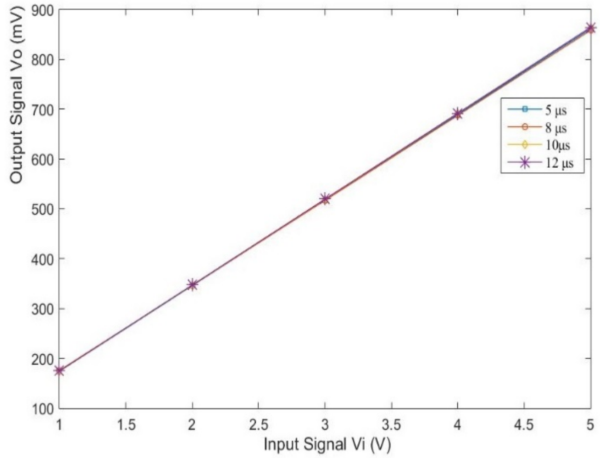

Figure 6: Vo vs. Vi fitted lines at different pulse widths.

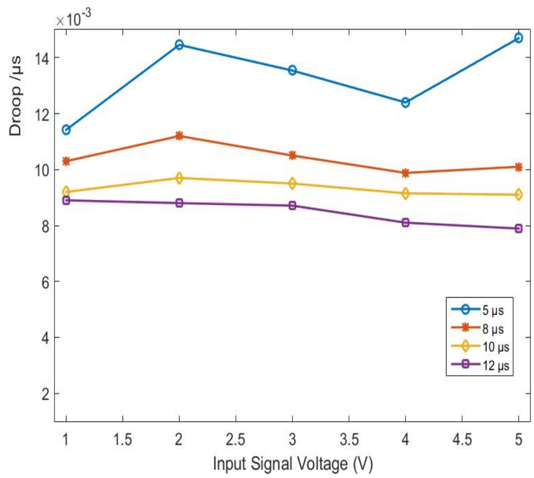

Figure 7: Curves of the droop at different pulse widths.

SHORT PULSE MEASUREMENT

The short pulse, whose repetition frequency is 33 MHz and pulse width is 0.1-1.1 ns, is generated by HP 8133A signal source. Figure 8 shows the waveform of the output signal at 1 ns pulse width. When the input signal is to short, the output signal inducted by beam current transformer will be distortion because of the limitation of rise time and fall time. So we can estimate the rise time and the fall time by comparing the voltage and the FWHM of the output signal with the input signal, shown in Figure 9 and Figure 10. The rise time is about 500 ps as well as the fall time, which is much better than the old CT's [4], with the ferrite magnetic core, whose rise time is about 30ns. Compared with the fast current transformer (FCT) produced by Bergoz Company, whose rise time is about 250 ps, the CT has the feasibility of measuring short pulse around 1 ns width.

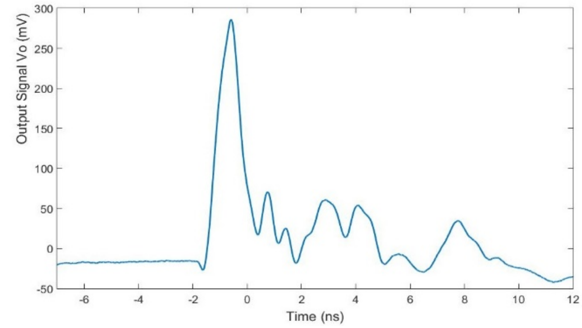

Figure 8: Waveform of a 1 ns short pulse.

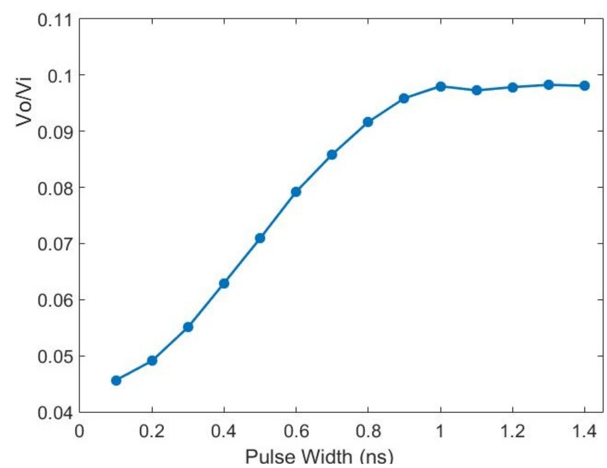

Figure 9: Curve of the radio of output and input signal voltage with the ideal pulse width.

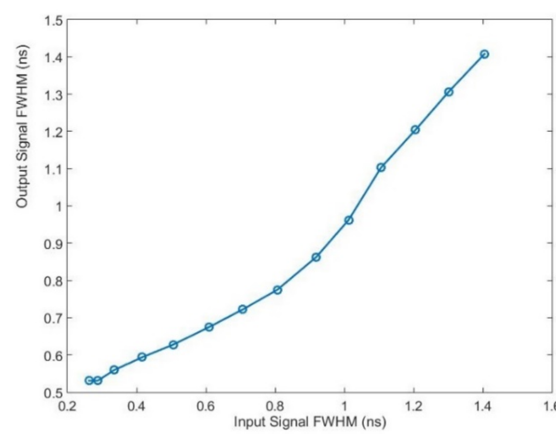

Figure 10: Curve of the inaction pulse FWHM with the input pulse FWHM.

CONCLUSION

We have introduced the new beam current transformer for the IR-FEL facility. It can meet the requirement of long pulse measurement. Meanwhile, its ability in measuring short pulse is improved a lot. Next, it will be installed on the beam line of the IR-FEL to do online test to verify its beam measurement capability.

REFERENCES

[1] H. J. Wei, Y. L. Yang, *et al.*,"Design of the diagnostic System for a New IR-FEL Facility at NSRL", *in Proc. IPAC'16*, Busan, Korea, paper MOPMB040.

[2] S. Q. Hao, "Process and Mechanism of Laminated Amorphous Magnetic Ring", A Dissertation for Master's Degree, Zhejiang Normal University 2014. (in Chinese).

[3] C. C. Cheng, Bao-gen Sun, *et al.*, "Design of Beam Intensity Measurement System in Injector for HLS II", *in Proc. IPAC'14*, Dresden, Germany, paper THPME141.

[4] B. G. Sun, P. Lu, J. H. Wang, *et al.,* Beam Measurement System in NSRL. *Journal of Systems Engineering and Electronics*, 2000.9, **11**(3): 9-13.

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