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PROTOTYPE OF WHITE RABBIT BASED BEAM-SYNCHRONOUS TIMING SYSTEMS FOR SHINE*

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Abstract

Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is under construction. SHINE requires precise distribution and synchronization of the 1.003086MHz timing signals over a long distance of about 3.1 km. Two prototype systems were developed, both containing three functions: beam-synchronous trigger signal distribution, random-event trigger signal distribution and data exchange between nodes. The frequency of the beam-synchronous trigger signal can be divided according to the accelerator operation mode. Each output pulse can be configured for different fill modes. A prototype system was designed based on a customized clock frequency point (64.197530MHz). Another prototype system was designed based on the standard White Rabbit protocol. The DDS (Direct Digital Synthesis) and D flip-flops (DFFs) are adopted for RF signal transfer and pulse configuration. The details of the timing system design and test results will be reported in this paper.

OVERVIEW

Owing to the wide range of applications of X-rays in the research fields of physics, chemistry and biology, facilities with the ability to generate X-rays were developed continuously in the last century. The free electron laser (FEL) is a novel light source, producing high-brightness X-ray pulses. To achieve high-intensity and ultra-fast short wavelength radiation, several X-ray FEL facilities have been completed or under construction around the world [1].

The first hard X-ray FEL light source in China, the so-called Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE), is under construction. It will utilize a photocathode electron gun combined with the superconducting Linac to produce 8 GeV FEL quality electron beams with 1.003086MHz repetition rate.

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SHINE timing system is design to provide precise clock pulses (Trigger) for drive laser, LLRF, solid state amplifiers, kicker, beam and optical instruments, etc. It will ensure the electron beam is generated and accelerated to the design energy, to produce the free electron laser, while completing the beam and optical parameters measurement and feedback. The White Rabbit (WR) technology was evaluated and will be adopted.

ARCHITECTURE

SHINE timing system is composed of one master node, WR switchs and more than 500 slave nodes. The master node receives reference signal from the synchronization system. The switches distribute the clock to all the nodes in the network using a hierarchical architecture. The node basic functionality comes in the form of an IP Core called WR PTP Core. They can be standalone trigger fanout modules or FMC boards, which can be embedded in the DBPM and LLRF processor. The system architecture is shown in Figure 1.

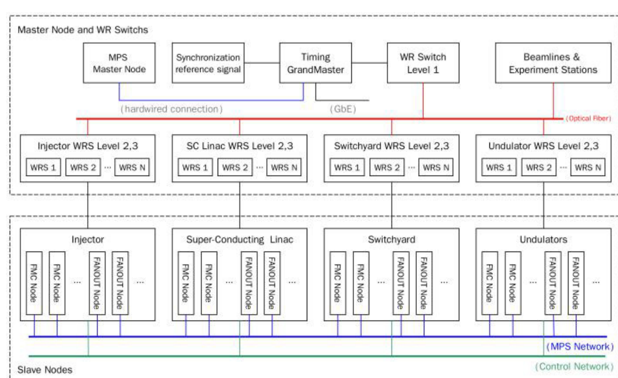

Figure 1: SHINE timing system architecture.

Three functions are designed: beam-synchronous trigger signal distribution, random-event trigger signal distribution and data exchange between nodes. The frequency of the beam-synchronous trigger signal need be divided according to the accelerator operation mode. Each output pulse need be configured for different fill modes.

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SHINE requires precise distribution and synchronization of the 1.003086MHz (1300/1296) timing signals over a long distance of about 3.1 km. The beam-synchronous trigger signal distribution is the basic and priority function.

The standard White Rabbit network operates at 125/62.5MHz clock. If the repetition frequency of SHINE is 1.0MHz, 1300 MHz RF reference signal can be divided to 10MHz as the reference signal. The salve nodes output the trigger signals at the specified time, such as 1us, 2us, 5us, etc. But the repetition frequency is 1.003086MHz, we need to find the new technical routes.

White Rabbit Trigger Distribution

White Rabbit Trigger Distribution (WRTD) is a generic framework for distributing triggers (events) between Nodes over a White Rabbit network [2]. WRTD nodes receive input events and distribute them to other nodes over WR in the form of network messages that are used to transfer the timestamp of the input event. The receiving nodes are programmed to execute some output event (action) upon reception of a particular message, potentially with some fixed delay added to the timestamp [3]. See Fig. 2:

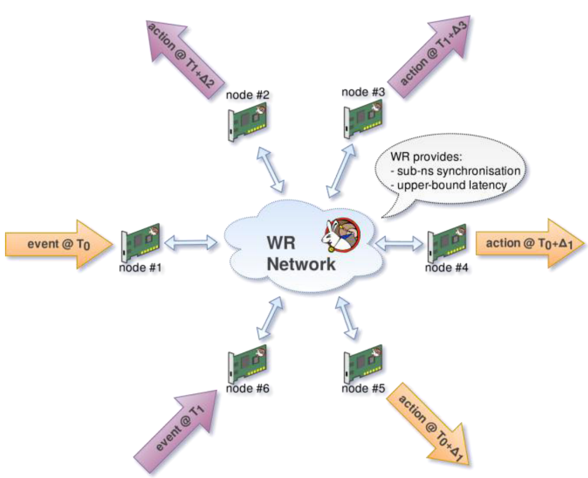

Figure 2: White Rabbit Trigger Distribution[2].

WRTD was used by CERN and SXFEL-UF (Shanghai soft X-ray Free-Electron Laser User Facility). The number of trigger sources in the system and the trigger repetition rate is limited by the network bandwidth and maximum acceptable latency requirements.[4] The SHINE beam-synchronous trigger signal could theoretically be distributed via WRTD, but the repetition rate too high. The 10 Gigabit White Rabbit switches are required, which are no commercial products yet.

The random-event trigger signal distribution is an extension function of SHINE timing system. It is used to distribute various event signals, such as beam loss, machine snapshot, etc. This function is achieved in our two prototypes by WRTD similar technology.

RF over White Rabbit

In White Rabbit network all nodes have the same reference frequency and time. The master node phase locks its DDS (Direct Digital Synthesis) to the RF input, and broadcast the DDS control words including a TAI timestamp. All slave nodes update their DDSes with the received control word at the same moment [4,5]. See Fig. 3:

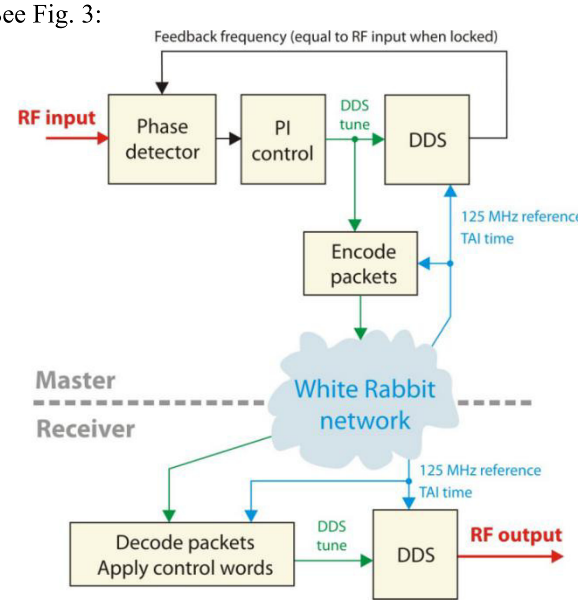

Figure 3: RF over White Rabbit[3].

This technology could be adopted for our beam-synchronous trigger signal distribution, but it needs further development. The slave nodes should output the low-jitter pulse signal. Meanwhile, it is expected that the pulses can be configured for different fill modes. We carried out the prototype (II) development with the state key laboratory of particle detection and electronics, University of Science and Technology of China[6].

Non-Standard Clock Transmission

The repetition frequency of SHINE is 1.0030864MHz. If we build a customized White Rabbit network with non-standard PTP core, we can use the frequency division of 1300MHz as the reference signal instead of GPS/Cesium clock. This was originally just an idea, verified by the prototype (I, II) development. The prototype I was completed in cooperation with with the department of engineering physics, Tsinghua University. This will implement the beam-synchronous timing system with more simpler architecture than RF over White Rabbit.

PROTOTYPE I DEVELOPMENT

The standard White Rabbit network operates at 125/62.5MHz clock, using the external 10 MHz reference signal. The center frequency of VCXO (Voltage-Controlled Crystal Oscillator) is 25MHz. In order to minimize the modifications to the standard White Rabbit equipment, the initial solution was to replace the VCXO of the switches and nodes and shift the operating frequency to 67.708305MHz (1.003086MHz×135/2). The

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system worked using the customized 27.083MHz VCXO, and less than 10ps jitters was achieved.

It is found that the frequency factor 135/2 is not conducive to the phase calculation and pulse delay. Therefore, the operating frequency was changed to 64.197504MHz (1.003086MHz × 64), which is easy to generate 2^N divisions and thus obtain machine clock. Meanwhile, this frequency can be configured from the standard VCXO (25MHz × 52/81), not the customized VCXO.

There is a clear proportional relationship between the standard second and the pseudo-seconds (~0.9969s). The machine clock phase relationship is also determined.

Standard time format:

[seconds : nanoseconds : sub-nanoseconds]

Non-Standard time format:

[pseudo-seconds : clock integer period : phase]

The prototype master node and slave node are shown in figure 4 and 5. The master node receives the random-event trigger signal input. Different functions can be enabled or disabled via the digital signal from MPS (Machine Protection System). The level 1 WR switch is configured as the Grandmaster mode, which receives the external reference and PPS signal.

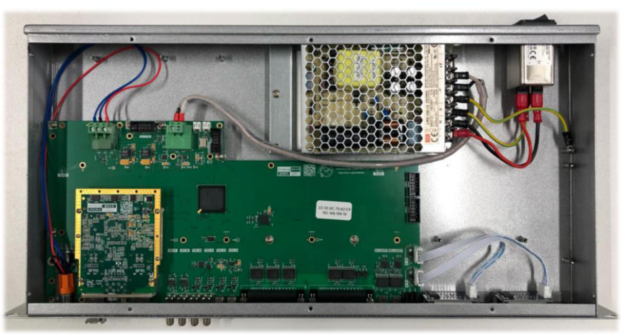

Figure 4: Prototype I master node.

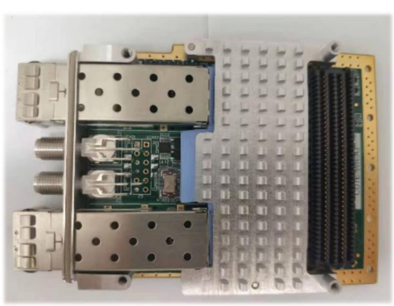

Figure 5: Prototype I salve node.

The slave node is FMC board (FPGA Mezzanine Card), which follows the ANSI/VITA 57.1-2019 standard. There are two SFP ports and two SMA connectors on the front panel. One SFP port is used to connect to the White Rabbit network and the other is in reserve. It will be used to connect to the standard network for status monitoring in the future. One SMA connector outputs the beam-synchronous trigger signal, the other can be configured as interlock input. More signal outputs are developed through the FMC connector, including 8 independent beam-synchronous trigger signal channels with adjustable delay and pulse width, 4 independent random-event trigger signal channels.

PROTOTYPE II DEVELOPMENT

Prototype II implements both the two technical routes: the non-standard clock transmission and RF over White Rabbit. The details of the latter are described below.

The system architecture is shown in Figure 6. Based on the standard White Rabbit network, the master node converted the 9.027778MHz (1.003086MHz × 9) RF signal into the frequency and phase information. Then the data is transmitted to all slave nodes. The slave nodes use the received date to recover the clock and realize precise distribution and synchronization of the machine clock.

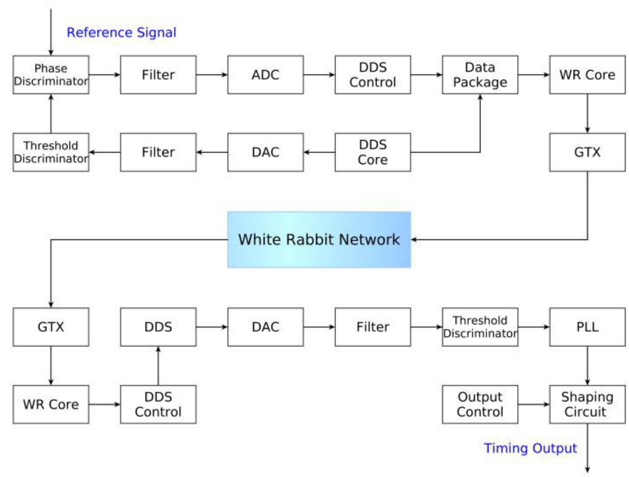

Figure 6: Prototype II system architecture.

The prototype master node and slave node are shown in figure 7 and 8. The master node is configured as the Grandmaster mode, which receives the external reference signal and random-event trigger signal. The standard WR switches are adopt to connect the slave nodes.

Figure 7: Prototype II master node.

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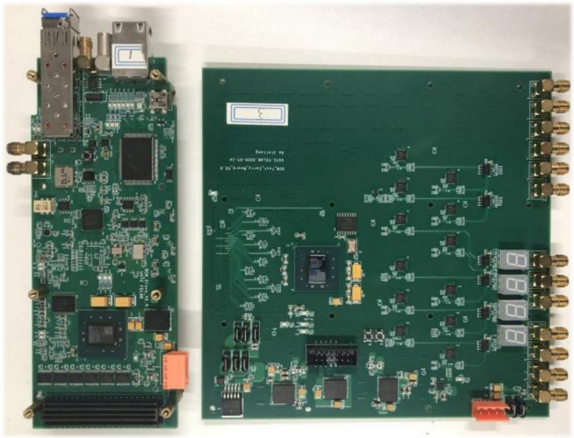

Figure 8: Prototype II salve node.

The slave node is a non-standard FMC card. It is used to verify multiple functions, including signal recovery, pulse output, frequency division, delay adjustment and so on. The diagram of fan-out and shaping circuit is shown in Figure 9.

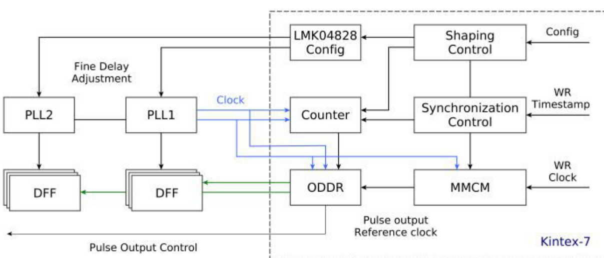

Figure 9: Fan-out and shaping circuit.

The circuit is mainly composed of the FPGA, off-chip PLL and DFF. The FPGA is responsible for frequency division, pulse width and coarse delay adjustment. The off-chip PLL is used for the signal fan-out and fine delay adjustment. The DFF latches the output of FPGA to ensure the quality and accuracy of the final pulse output.

TEST RESULTS

A series of tests were carried out to confirm the performance of the prototype. The following parameters are verified for beam-synchronous trigger and random-event trigger signal distribution.

- Jitter between the output of slave node and the external reference signal.
- Jitter between the outputs from different slave nodes.
- Skews between two slave nodes after powering up and down.
- Delay and pulse width adjustment.
- Temperature drift.

Prototype I Test

The test platform of Prototype I is shown in Figure 10 and 11. The GPS/Rubidium clock provides a stable 10MHz external reference signal for the arbitrary waveform generator, not for White Rabbit equipment. One channel of periodic square wave signal (1.003086MHz×16) is used as the non-standard external reference signal. The other channel is used as PPS signal after frequency division by DG645. The level 1 WR switch is configured as the Grandmaster mode. The computer is connected to the non-standard WR switch via the conversion module, which is used to set the parameters of the WR equipment. The Keysight MSOS604A Oscilloscope is used to measure the output of slave node and the external reference signal.

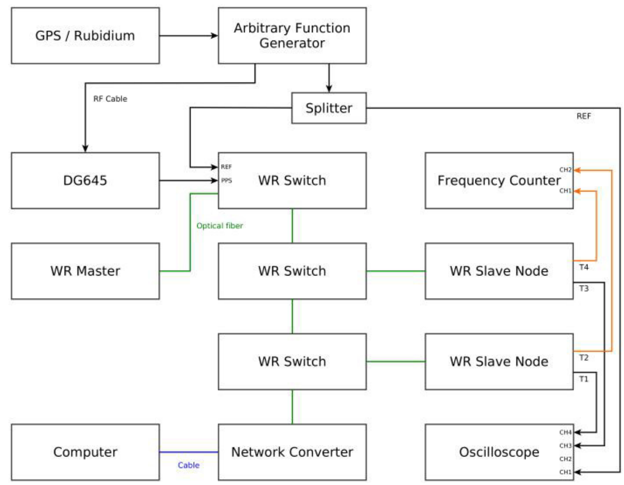

Figure 10: Prototype I test platform diagram.

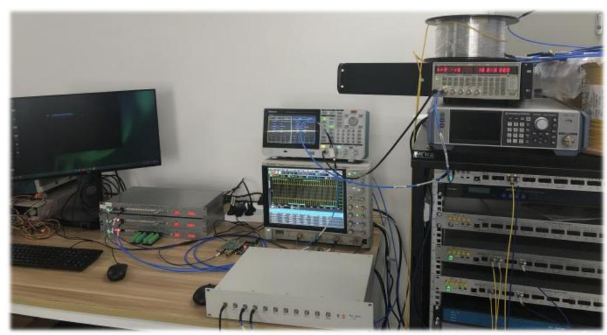

Figure 11: Prototype I test platform.

For the beam-synchronous trigger signal distribution, the jitter between the output of slave node and the external reference signal is less than 10ps. The jitter between the outputs from different slave nodes is less than 5ps. The temperature drift test results are shown in the figure 12. For the random-event trigger signal distribution, the jitter between the output of slave node and the external reference signal is less than 60ps.

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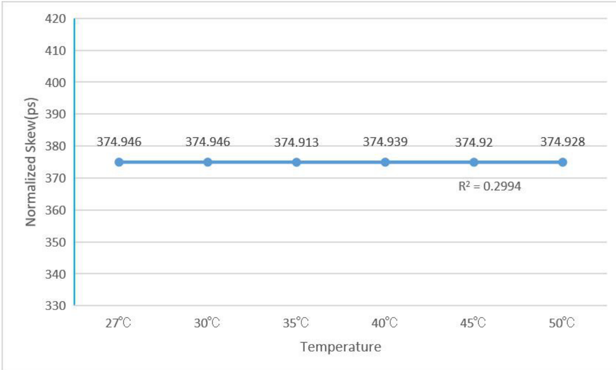

Figure 12: Result of the temperature drift test.

Prototype II Test

The test platform of Prototype II is shown in Figure 13. The GPS/Rubidium clock provides a stable 10MHz external reference signal for the arbitrary waveform generator and WR switch. The master node is configured as the Grandmaster mode, which receives the RF signal (1.003086MHz×9). The computer is connected to the WR equipment via the standard network switch. The Keysight MSOS604A Oscilloscope is used to measure the output of slave node and the external reference signal.

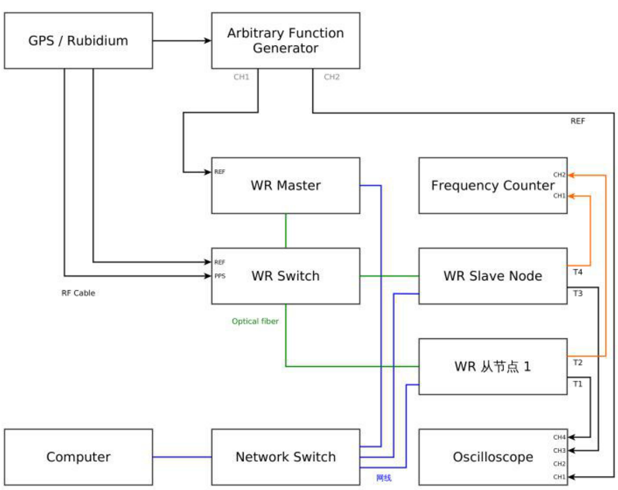

Figure 13: Prototype II test platform diagram.

For the beam-synchronous trigger signal distribution, the jitter between the output of slave node and the external reference signal is less than 20ps. The jitter between the outputs from different slave nodes is less than 10ps. For the random-event trigger signal distribution, the jitter between the output of slave node and the external reference signal is less than 35ps.

CONCLUSION

Two prototype systems were developed, both containing three functions: beam-synchronous trigger signal distribution, random-event trigger signal distribution and data exchange between nodes. The non-standard clock transmission was proposed and verified. The prototype development has just been completed and we will do further test and evaluation for the SHINE project.

ACKNOWLEDGMENT

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