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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 1.003086 MHz 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 (64.197530 MHz). 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, laboratory 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 consists of an 8 GeV continuous-wave (CW) superconducting RF Linac, 3 undulator lines, 3 following FEL beamlines, and 10 experimental end-stations. Main parameters are presented at Table 1.

SHINE timing system is design to provide precise clock pulses (Trigger) for drive laser, low-level RF, 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.

Table 1: Main Parameters of the SHINE

Parameter	Value
Beam energy	8 GeV
Bunch charge	100 pC
Peak current	1500 A
Max repetition rate	1.003086 MHz
Photon energy	0.4 - 25 keV
Total length	3.1 km

ARCHITECTURE

SHINE timing system is composed of one master node, WR switches and more than 800 slave nodes. The master node receives reference signal from the femtosecond optical 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 FPGA Mezzanine Cards (FMC), which can be embedded in the beam signal processors for the beam position, beam length, arrival time, beam loss and charge measurement. The system architecture is shown in Fig. 1.

There are three functions designed: beam-synchronous trigger signal distribution, random-event trigger signal distribution and data exchange between multiple nodes. The frequency of the beam-synchronous trigger signal needs to be divided according to the accelerator operation mode. The output pulse needs to be configured according to the filling pattern.

SHINE project requires precise distribution and synchronization of the 1.003086 MHz (1300 MHz/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 125/62.5 MHz clock. If the max repetition frequency of SHINE is 1.0 MHz, 1300 MHz RF reference signal can be divided to 10 MHz 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 1.003086 MHz, we need to find the new technical routes.

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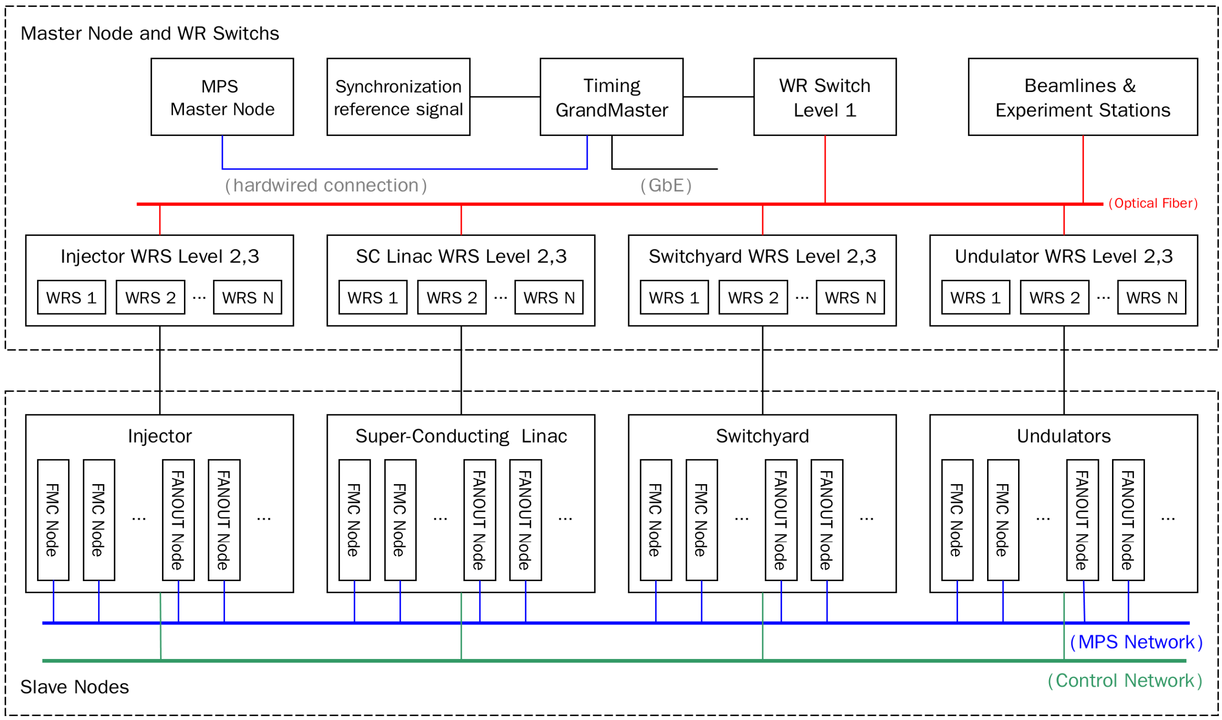

Figure 1: SHINE timing system architecture.

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 White Rabbit 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].

WRTD has been used at CERN BE 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 beam-synchronous trigger signal could theoretically be distributed via WRTD, but the max repetition frequency of SHINE is too high. The 10 Gigabit White Rabbit switches are required, but there is no commercial product 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. They are input from the master node. This function is implemented in our 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].

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 according to the filling pattern. 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 1.0030864 MHz. If we build a customized White Rabbit network with non-standard PTP core, we can use the frequency division of 1300 MHz 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 the department of engineering physics, Tsinghua University. This route can 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 125/62.5 MHz clock, using the external 10 MHz reference signal. The center frequency of VCXO is 25 MHz. In order to minimize the modifications to the standard White Rabbit hardware, the initial solution was to replace the VCXO of the switches/nodes and shift the operating frequency to 67.708305 MHz (1.003086 MHz × 135/2). The system worked using the customized 27.083 MHz VCXO, and less than 10ps (RMS) jitters was achieved.

It is found that the frequency factor 135/2 is not conducive to the phase calculation and pulse delay. Therefore, the

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operating frequency was changed to 64.197504 MHz (1.003086 MHz×64), which is easy to generate 2^N divisions and thus obtain machine clock. Meanwhile, this frequency can be configured from the standard VCXO (25 MHz×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 master node receives the random-event trigger and interlock 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.

The slave node is FMC LPC board, which follows the ANSI/VITA 57.1-2019 standard. There are two SFP ports and two SMA connectors on the front panel, as shown in Figs. 2 and 3. One SFP port is used to connect to the White Rabbit network and the other is in reserve. It can 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 the interlock input. More signal outputs are developed through the FMC connector, including eight independent beam-synchronous trigger signal channels with adjustable delay and pulse width, four independent random-event trigger signal channels.

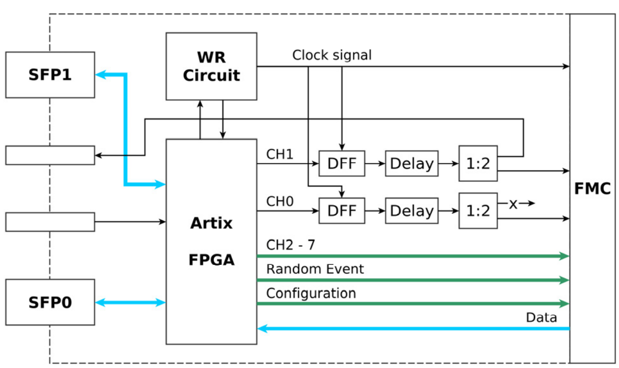

Figure 2: Prototype I salve node architecture.

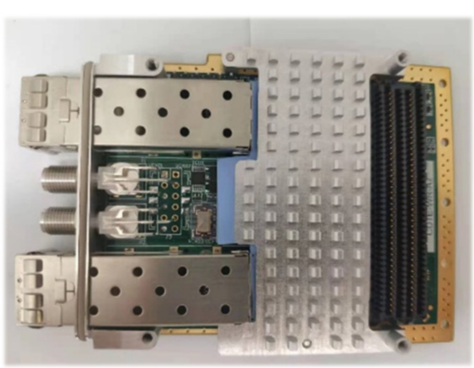

Figure 3: Prototype I salve node.

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 Fig. 4. Based on the standard White Rabbit network, the master node converted the 9.027778 MHz (1.003086 MHz×9) RF signal to 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.

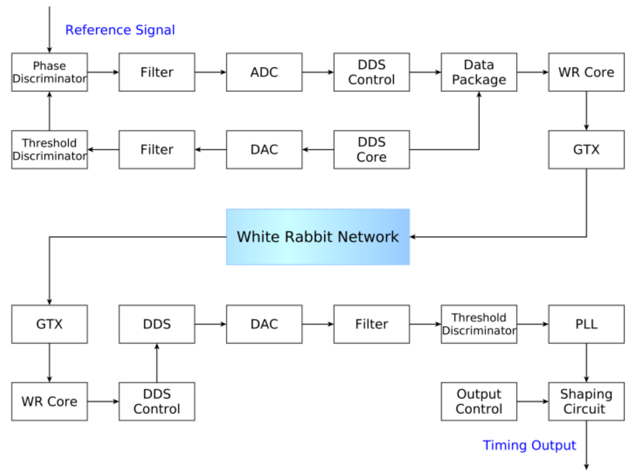

Figure 4: Prototype II system architecture.

The master node and slave node are shown in Figs. 5 and 6. 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.

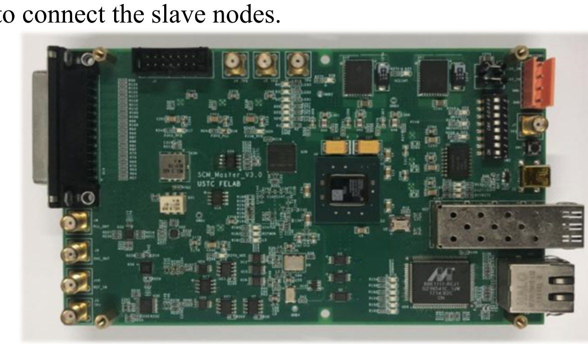

Figure 5: Prototype II master node.

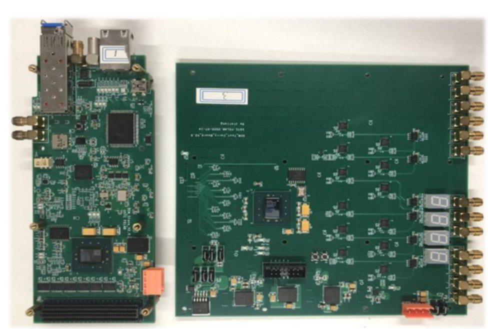

Figure 6: Prototype II salve node.

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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 Fig. 7.

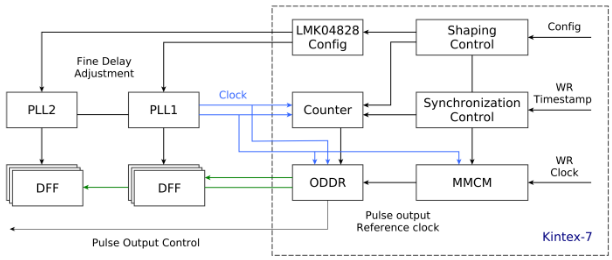

Figure 7: Fan-out and shaping circuit.

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.

PERFORMANCE

A series of tests were carried out to confirm the performance of the timing system. The following items 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 Fig. 8 and 9. The GPS/Rubidium clock provides a stable 10 MHz external reference signal for the arbitrary waveform generator, not for the White Rabbit switches or nodes. One channel of periodic square wave signal (1.003086 MHz×16) is used as the non-standard external reference signal. The other channel is used as PPS signal after frequency division by DG645 (SRS Digital Delay/Pulse Generator). The level 1 WR switch is configured as the Grandmaster mode. The laptop computer is connected to the non-standard WR switch via the conversion module, which is used for system parameter configuration. The Keysight MSOS604A and Siglent SDS6204 H12 Pro Oscilloscope are used to measure the output of slave node and the external reference signal.

Figure 8: Prototype I test platform.

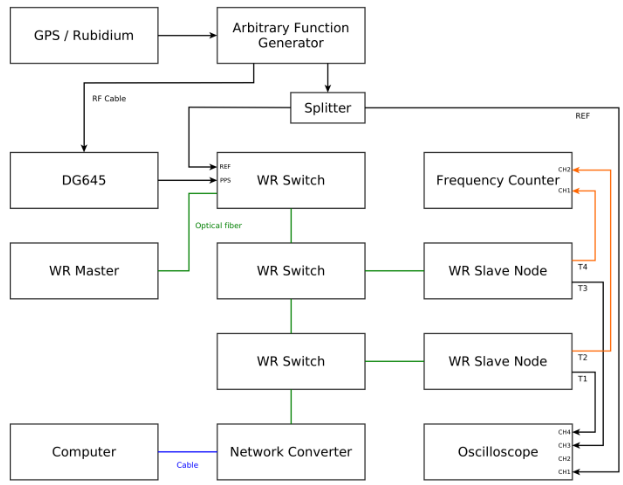

Figure 9: Prototype I test platform diagram.

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

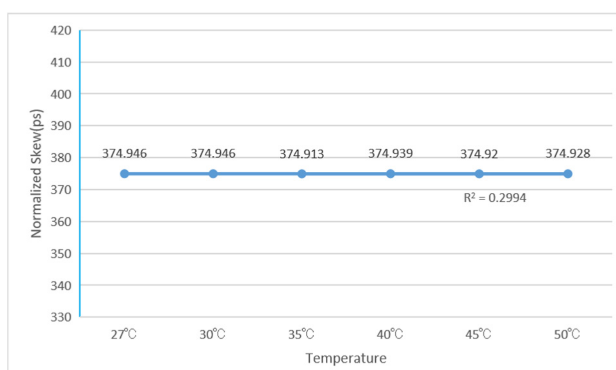

Figure 10: Result of the temperature drift test.

Prototype II Test

The test platform of Prototype II is shown in Fig. 11. The GPS/Rubidium clock provides a stable 10 MHz 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

(1.003086 MHz×9). The laptop computer is connected to the WR switches and nodes via the standard network switch. The Keysight MSOS604A and Siglent SDS6204 H12 Pro Oscilloscope are used to measure the output of slave node and the external reference signal.

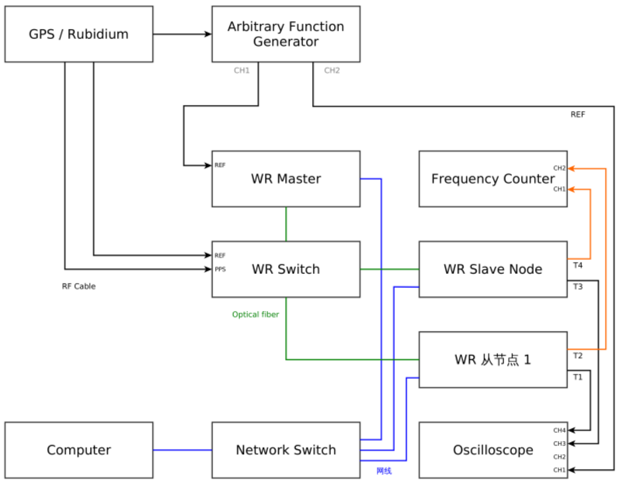

Figure 11: Prototype II test platform diagram.

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

CONCLUSION

The timing system is currently under construction. Two prototype systems were developed, both containing three functions: beam-synchronous trigger signal distribution, random-event trigger signal distribution and data exchange between multiple nodes. The non-standard clock transmission was proposed and verified.

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