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TIMING SYSTEM UPGRADE FOR TOP-OFF OPERATION OF HLS-II*

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Abstract

The Hefei Light Source II (HLS-II) is a vacuum ultraviolet (VUV) synchrotron light source. A major upgrade of the light source was finished in 2014, and the timing system was rebuilt with event-system to meet synchronization requirements of the machine. The new timing system provides about 100 output signals with various interfaces. The time resolution of this system is 9.8 ns for most devices and 9 ps for the electron gun and the injection kickers. The measured jitter of the output signal is less than 27 ps (RMS). In order to improve the performance of light source, the top-off operation mode has been planned. As part of this plan, both the hardware and the software of the timing system are upgraded. By obtaining real-time data of beam measurement of storage ring, the automatic selection of the bucket is implemented. With any designated bunch pattern, top-off injection is achieved, and the storage ring beam can be uniform filled well.

INTRODUCTION

The Hefei Light Source (HLS) at the National Synchrotron Radiation Laboratory (NSRL) is a second-generation synchrotron radiation light source, providing broad band radiation from IR to VUV for various user programs. In order to further increase its brightness, the light source was overhauled from 2010 to 2014. The upgraded light source, named HLS-II, is comprised of an 800 MeV linac, an 800 MeV storage ring and a transport line connecting the linac and storage ring.

In the upgrade, the HLS-II timing system was completely rebuilt to meet the synchronization requirements of the machine. It provides about 100 output signals to trigger accelerator subsystems, including the electron gun, solid-state amplifiers, modulators, injection septum and kicker magnets of the storage ring, etc. In addition, the timing system also provides RF and revolution frequency clocks for beam diagnostic stations. These clocks are phase-locked with the storage ring RF system to make the diagnostic devices work properly.

As the event-driven timing system developed by the Micro-Research Finland (MRF) Oy is widely used in many accelerator facilities all over the world, the MRF cPCI-series products are chosen for building the HLS-II timing system. The hardware schematic diagram of the system is illustrated in Fig. 1. As shown in the figure, the HLS-II timing system employs an event generator (EVG) card, cPCI-EVG300, as the master card to generate event codes. The RF signal with a frequency of 204 MHz is used as the input signal for the EVG card, and for phased-lock with the RF system. The input signal passes through a divider in the EVG card, and is used as the event clock to generate event codes. The event codes are sent to all event receiver (EVR) cards installed in Input/output controllers (IOCs) via a cPCI-FOUT12 fan-out card. Among these EVR cards, cPCI-EVR300 cards are used to generate common trigger signals, while cPCI-EVRTG cards are used to generate trigger signals with fine delay adjustment for the electron gun and injection kickers, and to reconstruct the RF and revolution frequency clocks for beam diagnostic stations.

Five IOCs are distributed in different locations to provide trigger signals for nearby systems. Each IOC of the timing system employs an Adlink cPCIS-6418U chassises to host a cPCI-6880 CPU board and MRF timing modules. The IOCs software, include hardware drivers, database records and operation interfaces, are stored in a remote virtualized server cluster, and shared through NFS protocol [1].

By commissioning and operation since 2014, the good performance of the HLS-II timing system is well confirmed. The test results show that the relative jittering between the EVR output and the RF signal is close to a normal distribution, the jitter width is less than 27 ps, and the maximum peak-to-peak value is about 180 ps.

BUNCH-BY-BUNCH INJECTION

Bunch-by-bunch injection is essential for stable operation and critical for user programs. To realize this injection scheme, the HLS-II timing system is configured to provide synchronization signals with proper delays for various systems [2]. As the timing modules only work with a frequency lower than 125 MHz, a frequency divider is used to acquire a 102 MHz signal from the 204 MHz input signal. This 102 MHz signal is used as the clock signals for the delay modules, and used as the input signal of a counter to produce the 1 Hz injection signal for the bucket chooser which is actually a delay unit. Both the frequency divider and counter are inhabited in the EVG card. The clock and injection signals are also used by various beam diagnostic apparatus to synchronize their measurements. Using pre-programed delays, the bucket chooser produces signals to trigger the electron gun, linac power supply system, and the storage ring injection system to aim the electron beam at a designated bucket.

Since the bucket chooser uses a 102 MHz signal as its clock, while the storage ring RF signal is 204 MHz, the delay time between two ticks of the bucket chooser equals to 2 bucket length. However, the harmonic number of the storage ring is 45, the bunch-by-bunch injection can be accomplished using proper bucket chooser delays. The count of delay ticks for the n^{th} bucket is given by Eq. (1).

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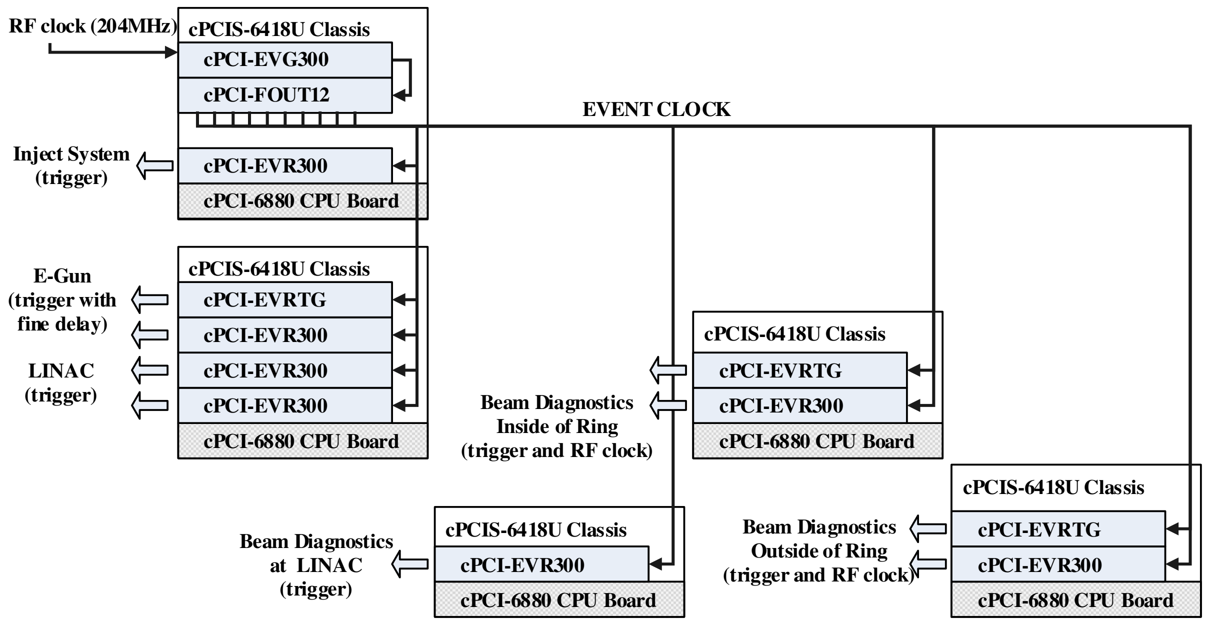

Figure 1: Overview of the HLS-II timing system.

$$
\begin{aligned}
t_n &= n/2,(n=0,2,4,\ldots,44);\\
t_n &= 22+(n+1)/2,(n=1,3,5,\ldots,43).
\end{aligned}
\tag{1}
$$

The functional diagram of the timing system is illustrated in Fig. 2. Each bucket can be enabled/disabled to be filled during injection. The enabled buckets can be automatically iterated or changed manually.

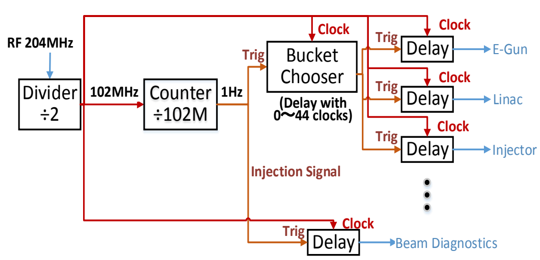

Figure 2: The functional diagram of the timing system.

HARDWARE UPGRADE

The top-off mode raises new requirement for timing trigger signal of the injection system. HLS-II uses 4 kicker magnets to create an injection bump for injecting the beam of the linear accelerator into the storage ring. The pulsed magnetic fields produced by these 4 kicker magnets are required to be consistence in waveforms and complete coincidence in time, otherwise they will produce residual oscillation besides the bump, causing disturbance to the beam in the storage ring [3].

In the decay mode operation, the synchrotron radiation light is not supplied to any experimental station when the storage ring is injected, and the residual oscillation will be attenuated rapidly by damping after injection. However, in the top-off mode operation, because users are studying continuously at their experimental stations at the same time of injection, the waveforms and time features of the 4 kicker magnetic fields should be adjusted more accurately, in order to reduce influences of the residual oscillation.

The waveforms of the 4 kicker magnetic fields can be pre-adjusted to meet the consistency, but the thyratron discharge switches of the magnet power supplies have discrete response time relative to the external trigger. It is necessary to precisely adjust the delay of each kicker so that the rising edges of their pulsed magnetic fields completely coincide. The pulse width of the kicker magnetic field is about 1.3us, and the delay adjustment minimum step is required to reach 1ns. The injection system itself lacks remote adjustment means with this precision, thus the timing system is asked to finely adjust the trigger signal delay.

In the initial design of timing system, the cPCI-EVR-300 board is selected as the output board of the injection system trigger signal. The delay adjustment minimum step is equal to the reciprocal of the external clock frequency (for HLS-II, the value is 1 / 102MHz ≈ 9.8ns). In order to adjust the delay of the kicker trigger signal more finely, the cPCI-EVRTG board is used to replace the cPCI-EVR-300 board. Besides the same delay adjustment function, each output channel of the new board has an addtional programmable delay line between the FPGA and the actual output, allowing a delay range of 1024 steps with approximately 9ps each step [4].

Using both the clock counter and the programmable delay line of the cPCI-EVRTG board, the delay range of the trigger signal can be adjusted more than 1s (the injection repetition period), while the delay minimum step is less than 10ps. By this way the time consistency of the 4 kicker magnetic fields can be accurately adjusted (Fig. 3), which reducing the influences of the residual oscillation on the beam in the top-off mode operation.

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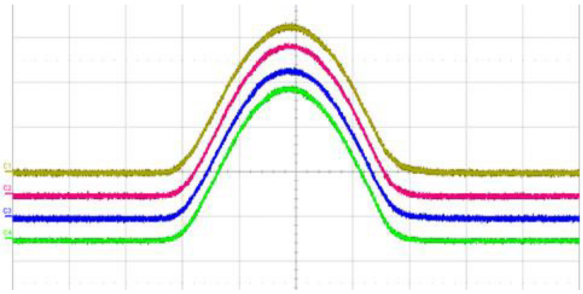

Figure 3: Time consistency of the 4 kicker.

SOFTWARE UPGRADE

In the original decay mode operation, the timing system provides accurate timing triggering signals to the beam measurement system and the injection system (including the electron gun), respectively. These systems receive the triggering signal and initiate each independently established work process without feedback any data to the timing system. However, in top-off mode, we need to obtain real-time beam current data of each bunch measured by the beam measurement system. And according to these data, the automatic selection of the bucket is realized.

In order to deal with the requirement of top-off mode operation, we modified the timing system software, adding a special function to calculate the difference between the beam current of each bunch and its set value, so that to judge which bucket should be injected in next cycle. Then the delay of the event, which trigger the electron gun and injection system, is set with the corresponding value. But in the initial test, the program did not work properly. The bucket that we expect to be selected at some moment, is actually injected after 2 cycles. (The delay is 2s as the inject repetition frequency is 1 Hz).

Analysing the actual physical process, we found where the bug is. Each time the cycle is started, the injection process of the injection system (including the electron gun), the measurement process of the beam measurement system, and the judgment process for selecting the bucket, are all started and completed almost simultaneously after receiving the trigger signal. The trigger signals between these three systems are only synchronized. There is no restriction on their delay to meet the correct logical relationship, "injection——measurement——judgment".

Considering the damping process of the injection beam in the storage ring, the trigger signal of the beam measurement system is delayed by approximately 88ms (equivalent to 400,000 revolution turns of the beam in the storage ring). This ensures that the measured bunch current data correctly contains the latest injection beam. On the other hand, the judgment process is delayed by 0.5s (half a cycle) to ensure that the injection process and the beam measurement process of the latest cycle are totally completed, and that the bucket is selected based on the latest measurement.

After modified mentioned above, the bucket selecting process works very well. In each injecting cycle, the most being "needed" bucket is selected just in time. The comparison between Fig. 4 and Fig. 5 shows that the uniformity of the bunch filled in the storage ring is greatly improved when the bucket selection process based on the beam measurement results is used, which means that the quality of the synchrotron radiation light is better. (Bucket 1-5 and 40-44 are disabled to be filled.)

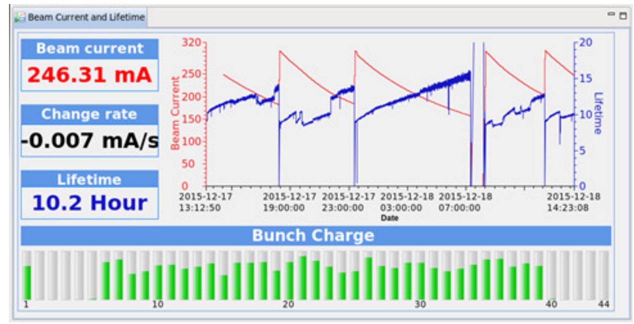

Figure 4: Injecting bucket by turns in decay mode.

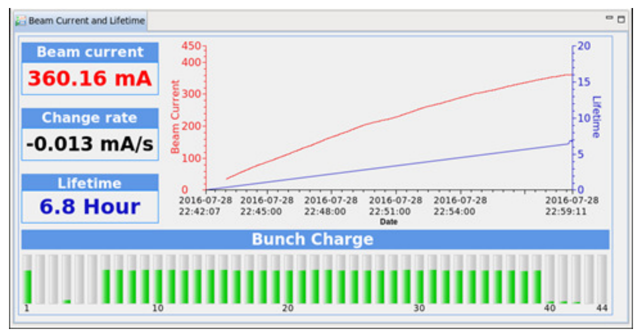

Figure 5: Selecting bucket based on beam measurement.

SUMMARY

The HLS-II timing system is developed using the cPCI-series event-driven products manufactured by the MRF Oy. In order to meet the top-off mode operation requirement, both the hardware and the software of the timing system are upgraded. The time consistency of injecting kickers can be more accurately adjusted to reduce the influences of the residual oscillation on the beam. By obtaining real-time beam current data of each bunch in the storage ring, the automatic selection of the bucket is implemented. With any designated bunch pattern, top-off injection is achieved, and the storage ring beam can be uniform filled well.

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