DEVELOPMENT OF TIMING AND CONTROL SYSTEMS FOR FAST BEAM SWITCHING AT KEK 8-GEV LINAC

K. Furukawa*, M. Satoh, T. Suwada, KEK, Tsukuba, 305-0801, Japan
T. Kudou, S. Kusano, MELCO SC, Tsukuba, 305-0045, Japan
A. Kazakov, GUAS/SOKENDAI, Tsukuba, 305-0801, Japan
G. Lei, G. Xu, IHEP, Beijing, 100049, China

Abstract

The 8-GeV linear accelerator (Linac) at KEK provides electrons and positrons to the Photon Factory (PF) and B Factory (KEKB). Simultaneous top-up injections for both PF and KEKB rings have been considered for improving injection efficiency and experimental stability. To provide these injections, fast beam-switching systems are being installed by upgrading the existing timing and control systems. While the old timing system provides precise timing signals for 150 devices, many of those signals are now dynamically switched using an event system. A new scheme has been developed and tested to enable double-fold synchronization between rf signals. Fast controls of the low-level rf system, beam instrumentation, kickers, gun, and beam operation parameters have also been upgraded for the fast and precise tuning of those parameters. The system has been under development since 2006, and is being deployed for beam operation in 2008.

INTRODUCTION

The KEK Linac injects electron and positron beams with different characteristics into four storage rings: KEKB-HER, KEKB-LER, PF, and PF-AR. It takes 30 s to 2 min to change the beam mode, depending on the degree of magnet standardization [1]. For example, when a beam development study is performed in the PF ring, the experiment at KEKB is disturbed. Owing to the crab cavities installed at KEKB, luminosity tuning is sensitive to the beam conditions at the both HER and LER rings. Therefore, it is preferable to ensure the simultaneous injection of beams to these rings. There is an increasing demand for top-up injection in the PF ring in order to obtain high-quality experimental data.

In view of the above requirements, a system that can rapidly switch between beam modes has been designed and implemented [2]. Many hardware components, such as pulsed magnets and fast microwave systems, have been installed in this system. The designing of beam optics is also performed in parallel to support the wide dynamic range of the beam energy and charge, namely, 3-times different energy and 100-times different charge.

The control and timing systems have also been upgraded in order to meet the requirement for performing beam-mode switching at 50 Hz (20 ms). An event system has been introduced so that the entire 600-m Linac can be notified of a switching event [3]. The system has been undergoing testing since 2006 and is expected to commence operation in autumn 2008.

* <kazuro.furukawa@kek.jp>

FAST BEAM-MODE SWITCHING

The Linac employs several beam modes. It took more than 30 s to switch more than 20 items. The following beam modes are considered the most important modes for fast beam-mode switching:

- KEKB HER: 8-GeV electrons, 1.2 nC, 2 bunches
- KEKB LER: 3.5-GeV positrons, 1.2 nC, 2 bunches (10-nC primary electrons)
- PF ring: 2.5-GeV electrons, 0.1 nC, 1 bunch

Here, 2 bunches in a beam pulse are separated in time by 96 ns. The fast switching of the above beam modes was challenging because the dynamic range of the beam characteristics is very large. An adaptive beam optics scheme has been developed to overcome the challenges. In order to implement this scheme, several hardware components have been improved. The parameters of system components listed below are changed within a period of 20 ms.

- Magnets: a pulsed bending magnet, several pulsed steering magnets, and a pulsed positron capture coil
- Microwave: phase and timing of low-level rf (LLRF) signals and timing of high-power rf signals
- Gun: selection between grid-pulsers, bias voltage and picosecond timing
- Beam instrumentation: synchronized and fast beam-position-monitor (BPM) readout, pulse selection for wire-scanners and streak cameras
- Injection: selection of septa and kickers, interface to bucket selection systems
- Operation: beam stabilization feedback, beam-mode sequence pattern generation, mode-dependent parameter manipulation and archiving

In order to achieve synchronized control over Linac and beam transport lines for KEKB and PF, a global event notification system has been installed. Errors in control are not acceptable because of safety reasons. Safety is an important issue since the beam powers vary by a factor of 10 to 100 [4]. It should be easy to manipulate the parameters for each mode to optimize beam tuning and the conditions for physics experiments. The easy manipulation of parameters for several beam modes is almost equivalent to building of several virtual accelerators.

EVENT NOTIFICATION SYSTEM

In the old system, beam modes were broadcast through two mechanisms. Four separate cables were connected to important control stations in order to broadcast four independent pulse characteristics: beam existence and the synchronized beam measurement. Detailed information was transferred using standard control features through control networks. Timing signals were transferred to 15 timing stations through a coaxial cable, which transmitted a 50-Hz pulse and a 571-MHz clock signal [5].

When the beam mode was changed, more than 500 parameters were changed. The switching took over 30 s mainly because many magnets had to be standardized.

The series-230 event system that was developed for Diamond light source was introduced in the new event notification system [6]. In this event system, an event generator (EVG230) is installed at the central station and event receivers (EVR200/EVR230RF) receive information through optical fibers. Each EVR can provide the following:

- A sequence of programmed events in a pulse
- A regenerated clock signal (in our case, 114.24 MHz)
- Up to 14 delayed timing signals (with a precision of less than 10 ps)
- Shared data buffer up to 2 k-bytes

Since the signals are transmitted using a single fiber connection, the maintenance of the signal quality is expected to be straightforward.

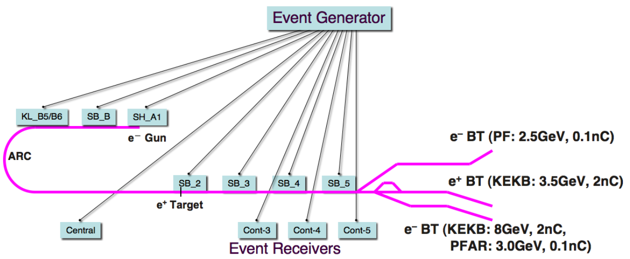

Figure 1: Layout of the new event system.

Figure 1 shows 11 EVRs installed along the Linac. These EVRs are believed to be sufficient for the control of three beam modes. Seven of these EVRs are located close to the existing timing stations, whose functionalities will be taken over by those EVRs. Consequently, the number of components in the system will reduce since an EVR can generate 14 precise delayed timing signals. Thus, most of the remaining old timing stations will be replaced by EVRs in the near future. Some devices such as streak cameras require high timing precision. For this purpose, a precise re-synchronization module is being developed.

The event rate is chosen to be 114.24 MHz, which is identical to the frequency of the first sub-harmonic buncher and $1/25^{th}$ of the main Linac frequency. The rf signal of 114.24 MHz is fed into the EVG230 and used to transfer events and other data to EVRs that are arranged in a star-like topology. Most of the EVR stations are connected through fan-out modules with multi-mode optical fibers that were laid more than 10 years ago. Some of further EVR stations are connected with single-mode optical fibers; small-form-factor pluggable (SFP) modules were replaced at the fan-out modules and EVRs.

The EPICS driver software is used and is extended to support the new features of the series-230 system. The CPU and the operating system of the VME computers for EVG/EVR are MVME5500 and VxWorks-5.5.1, respectively. This combination was chosen to satisfy the requirements of real-time operation of the system.

BEAM-MODE PATTERN GENERATION

Approximately 50 event codes have been defined so far. Some of them directly correspond to one of the beam modes, while some others correspond to a component of the accelerator equipment. A beam pulse is generated every 20 ms, and it is accompanied by a sequence of several event codes. The codes contain information on at least one event related to the beam mode of the present pulse and that of the next pulse. Some event codes received at an EVR station trigger the EPICS software to control the equipment connected to it.

Some of the equipment can respond to 50-Hz controls. However, other equipment responds to a restricted set of pulses. The beam-pulse request from each ring depends on the beam conditions and experimental conditions in the ring. Thus, the design and arbitration of the beam-mode train pattern is a complex task.

Since the modification of the software on the EVG system may interrupt the beam operation, it was decided to generate the pattern using a separate program. The present pattern generation scheme has been implemented using a scripting language in order to enable rapid prototyping.

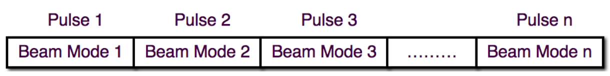

Figure 2: Beam-mode pulse pattern. A specific beam mode is assigned to each beam pulse, and several event codes accompany each beam mode.

A pattern such as Fig. 2 is designed using the program. The length of the pattern should be less than 500 pulses (10 s), and the pattern can be downloaded into the EVG system at any time. Once a pattern is loaded, it repeats until it is replaced. The new pattern replaces the previous one at the end of the pattern. The EVG system automatically generates an event code sequence following the beam-mode pattern.

EQUIPMENT CONTROL

EVR modules directly drive timing signals in response to event codes. The timing delays are modified according to the event codes that correspond to a particular beam mode. These timing signals are fed to devices such as pulsed magnets, LLRF systems, high-power sources, beam instrumentation, and injection systems in order to adjust the beam characteristics.

The LLRF parameters are essential in order to define the profile, absolute value and spread of the beam energy. At the end of each pulse, the LLRF parameters are changed to produce the next LLRF pulse, as in Fig. 3.

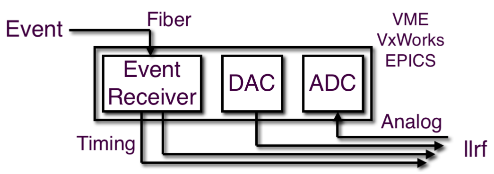

Figure 3: Six LLRF stations are managed by EVR systems.

Currently, the following six pulsed magnets are installed in Linac: a bending magnet to feed the beam to the transport lines, a pulsed coil to efficiently capture positrons, and pulsed steering magnets to guide the beam around the positron target by creating a beam orbit bump. These magnets are separately triggered by timing signals from nearby EVR systems, depending on the beam mode.

The beam instrumentations are also important for obtaining the desired beam properties. Approximately 100 BPMs are utilized to monitor, stabilize, and analyze the beam [8]. The old system reads the beam positions only once in a second. However, the beam characteristics must be acquired for every pulse when the beam is switched.

The new system employs 24 oscilloscopes (Tektronix DPO7104) [9]. EPICS software is embedded on to those oscilloscopes, and it can acquire the BPM signals in 10 Gsamples/s and analyze the beam properties by using more than 20 coefficients per BPM. They can process the signals for every pulse, recognize the beam modes, and distinguish between two bunches that are 96 ns apart. Since the event system cannot be embedded in the oscilloscope, event information is delivered through the normal control network.

For some of the beam instrumentation such as streak cameras that do not recognize 50-Hz switched signals, a timing signal is delivered only for a selected beam mode.

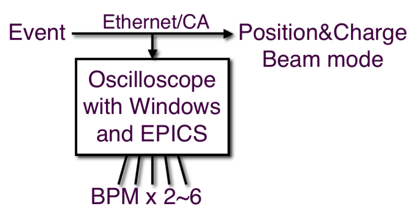

Figure 4: Twenty-four oscilloscopes are installed in order to read 100 BPMs at 50 Hz, recognizing the beam modes.

RF SYNCHRONIZATION

The rf frequencies in both rings are independently and continuously adjusted in order to compensate for the variations in the ring circumference. KEKB and Linac frequencies have a common source because the tolerance of the injection timing jitter is less than 30 ps. For the PF ring, a double-fold synchronization module was developed in order to choose a timing that synchronizes the PF revolution frequency and the Linac frequency within a certain jitter. Currently, the jitter is set to 300 ps.

CONCLUSION

The features of this new event-based control system are being evaluated in the beam operation. It has been proved that the system satisfies the requirements for fast beam switching. The system is expected to provide sensitive and stable tuning of KEKB with crab cavities for simultaneously achieving higher luminosity and a top-up injection to the PF ring. Further software development may be required to support the beam operations with those three virtual accelerators enabled by the event system. An integrity monitor is being developed for the system in order to ensure satisfactory operation.

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