REVIEW OF ACCELERATOR TIMING SYSTEMS

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Abstract

Practically every accelerator requires some kind of timing and synchronization. In this article, the technologies used in and relevant to timing systems, concepts of event timing and counter-based systems and approaches adopted at various accelerators are reviewed. The requirements concerning stability, precision and flexibility differ and a number of solutions to fulfill the needs are presented. A summary of aspects concerning timing and accelerator operations (injection, top-up, diagnostics, etc.) and the interface to other parts of the control system is presented.

1 INTRODUCTION

The task of a timing system is to synchronize all the (relevant) components in a possibly very large accelerator complex. One part of this task usually is to control the injection by triggering the particle source (gun) and firing the transfer line components like injection and extraction pulsed magnets at correct times. Also beam diagnostic components like beam position monitors, current transformers, profile monitors and so on have to be synchronized to the passage of the beam. As this has to happen with great precision and often with fine time resolution, this is often called the “fast timing”.

Other tasks for the timing system are related to synchronizing components where the resolution requirement is more relaxed, for example triggering the magnets for an acceleration ramp. Also triggering operational sequences like the filling of a storage ring, a sequence of measurements and synchronized orbit bumps belong to this category. These tasks are often referred to as “slow” or “software” timing. Another common application of a timing system is to supply time stamps to the control system processes, for example to enable correlating measurements that were done simultaneously at different locations.

A variety of methods is applied at different accelerators to achieve these goals. The approach taken to the synchronization depends on the required resolution and accuracy and also on the size of the accelerator complex. In some cases only one level of accuracy can meet all needs; a combination of fast and slow timing methods is used otherwise.

Little commonality has been achieved in the design of timing systems although the tasks are very much the same in all accelerators. However, some common philosophies and technical solutions that are common to almost all accelerators can be found. One of the aims of this paper is to point out the common features and hopefully also to inspire to find a more common approach.

2 TASKS OF TIMING SYSTEMS

2.1 Fast Timing

One of the main tasks of a timing system is to control the injection procedure. This type of synchronization mainly involves fast beam handling devices (electron gun, pulsed magnets) etc. and diagnostic devices like beam position monitors, current transformers, gated cameras and so on.

The injection control requires generation of reference signals (fiducials) for the synchronization like signal that indicates the revolution frequency of a storage ring or a signal when the particle source is triggered. These signals are usually generated from the main RF reference signal by downconversion (counting) to ensure phase locking to the beam timing. The signals are also commonly synchronized to the AC power line phase. The generated fiducials need to be transmitted to the equipment locations; there are a number of methods that are applied and they are given a closer look in the next chapter.

To fill a storage ring, the particle source (gun) has to be triggered; after (pre-)acceleration the beam has to be transferred to a storage ring, either at the final energy or for further acceleration. The beam transfer may have several stages depending on the layout of the accelerator complex. The task of the timing system is to match the delays between the gun triggering and the firing of the injection pulsed magnets so that the bunch is transferred to the correct RF bucket in the targeted accelerator. To fill the ring, the delays usually need to be adjusted several times to fill all the required buckets. This is often achieved with a synchronous counter that counts RF clock pulses; e.g. [1], [2]. To inject to a selected bucket, the bucket number (with possible offsets) is loaded to the counter, which generates an output pulse when the terminal count is reached. This method is conceptually simple and reliable. The technological difficulty of the implementation depends on the RF frequency; however with modern technology most of the accelerator operating frequencies can be covered.

2.2 Slow timing

In principle the tasks of the “slow” timing are no different from those of “fast” timing. The principal difference is that the time resolution requirement is more relaxed. In addition there are often other types of tasks for the slow timing like triggering software actions where the precision requirement is not so high. For example, the slow timing is often used to schedule the injection and measurements by adjusting the delays in the fast timing system. Often the dividing line is (in electron machines, at

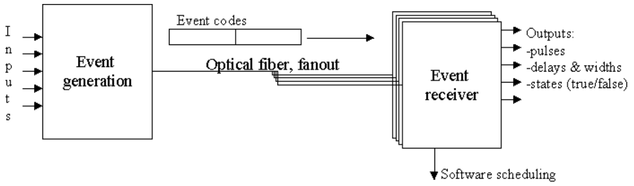


Figure 1. The principle of an event system

least) that the slow timing takes care of synchronization that is in the timescale of one storage ring revolution and the fast timing up to a single bunch level.

The number of components synchronized by the slow timing is usually large and this dictates the selection of technology. In most cases the cost to use the fast timing components for all tasks would be prohibitive.

One more common application for the slow timing is to provide time stamps for the measurement data so that they can be correlated across different locations around the accelerator. The timing system may assist to keep the time stamps across different equipment controller CPU’s synchronized.

3 TECHNOLOGIES

3.1. Technology decisions

The technology decisions to be made when developing a timing system are the method and media of signal distribution, the approach to device synchronization and how to adjust the timing of different components. The requirements of the accelerator operation naturally dictate the choices in most cases.

For device synchronization the timing fiducials have to be transmitted to the device locations over the plant. A number of different technologies have been applied. The common and the most straightforward method is baseband distribution, where the RF signal and timing fiducials are created in a single location and distributed as such, using either copper cable or an optical fiber [2]. The final synchronization is then done with a synchronous counter to restore the phase locking to the RF. This technique can be applied to high frequencies and can achieve very high precision. The drawback is however that the distribution tends to be costly, requiring a large number of cabling, transmitters and receivers. This method is usually applied only in the fast timing, for transmission of the most vital signals.

Modulated transmission where the fiducials are encoded by onto a carrier signal is also often applied. The main synchronization clock (RF or a phase locked subharmonic) serves as the carrier and the fiducials are recovered from the data stream with special receiver modules [fermi],[tesla]. This method simplifies the field wiring and thus reduces the cost. But for high RF frequencies it is difficult to achieve a timing resolution that would fulfill all needs with this method.

In the design of Fermilab [7], modules are provided that decode the global clocks and the events encoded on the global clock using Manchester encoding. These modules provide timing signals to equipment, synchronization to software (interrupt facility) and hardware assisted timestamps.

The idea of an event system is basically the same than in the modulated reference transmission. The timing fiducials are encoded to event codes in an event generator, which then serially transmits the codes over the plant[lhc]. There are variants in which operation events are transmitted continuously [slac] or only when a fiducial signal occurs at the generating side. An elegant example of the latter type is the APS event system [4]. It consists of an event generator card that accepts hardware and software trigger inputs. The input triggers are encoded to 8-bit event codes and transmitted (with fan-out) to a number of event receivers using an optical fiber. The event receivers can be programmed to handle the received events in different ways. The receivers have a number of different types of outputs, including fixed width pulses (up to 14), delay channels and set-reset outputs. The receivers also can generate VME interrupts to facilitate software scheduling and a mechanism to create hardware-assisted timestamps. The APS event cards are well integrated in the EPICS control system, providing flexible hardware triggers, triggering software (channel processing) and a hardware assisted high-resolution timestamp mechanism. The APS design was also selected for the Swiss Light Source (SLS), however with an upgraded design with faster components but still retaining the software compatibility.

The time resolution that can be achieved with an event system is dependent on the frequency with which these event codes can be transmitted. For example, the SLS event system uses gigabit link transmitters and receivers to transmit a 16-bit word (frame) at a frequency of 50 Mhz [5]. This design achieves a resolution of 20 ns between two consecutive events (and in generated delays and widths).

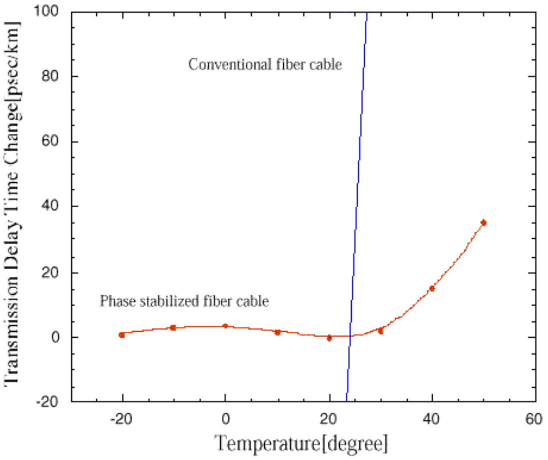
The limitation of this type of event system is that only one event can be transmitted at one time. When two events overlap in time a priority resolution has to be adapted and the signal with the lower priority suffers jitter of (at least) one event period. For this reason event systems alone are often not suitable for transmitting multiple reference fiducials. This limitation was overcome in the SLS event system design by using half of the link bandwidth for a "distributed bus" where input signals are sampled at every frame clock cycle and the status of the bits is transmitted with the frame. The 8-bit events are transmitted independently in the other half of the frame. Thus, up to eight signals can be transmitted simultaneously with the frame rate time resolution. By phase locking the signals to the transmission clock, they can be transmitted (essentially) jitter-free.

When the resolution is sufficient, an event system can take all the tasks of the timing system [6].

3.2. Timing reference stability

Regardless of the method used to distribute the timing fiducials, drifts in propagation delays may become problematic if the installation is large. Any thermal drifts affecting the cables cause slow phase drift also in the timing signals. This could be overcome by temperature control of the timing cables; however, when the plant is very large or otherwise a precise temperature control is difficult to achieve, a noteworthy solution is to use phase-stabilized optical fiber [2]. The idea of the phase-stable fiber is to have the core and clad materials of the fiber with different temperature coefficients so that they cancel each other. The achieved temperature coefficient is then about 0.04 ppm/°C, which corresponds to about 1.3 ps/°C/km; the corresponding figure for a normal fiberoptic cable is about 74 ps/°C/km [15] and for a phase-stabilized coaxial cable (HELIAX LDF2-50) about 19 ps/°C/km [13]. The downside of the phase-stable fiber is however that as a special product it is only manufactured according to demand and for small installations it may be difficult to get the required volume. The fiber is also expensive when compared with normal fiber.

A development to further improve the reference distibution stability with a feedback system is underway at KEKB [14].



The temperature coefficient of the phase-stabilized optical fiber (from [2]).

When the signal distribution is done with an optical fiber, the signals have to be converted from electrical to optical and at the receiving end back to electrical. The conversion causes extra jitter and phase shifts that have to be considered when evaluating the system performance. There exists a number of high-performance fiberoptical transmitters available on the market [11],[12] so a custom design is not necessarily required if the price-to-performance ratio meets the requirements. As usual, the price goes up with performance.

3.3. Precision requirements

The required time resolution depends mainly on the RF frequency of the accelerator. The control of one particle bunch or one RF bucket is usually the smallest required unit of accuracy. For example, to trigger an electron gun for a linac there is no need to have smaller steps than the RF, because the phase of the subsequent components can (and have to) be adjusted to the bunch timing with great precision. With many light sources and electron storage rings the RF frequency is around 500 MHz, which is well within reach of the present digital technology. To achieve better than RF resolution, analog delay methods are used in combination with digital ones to improve the resolution; this however comes often with an increase in jitter. Furthermore, if the delays run based on an internal clock reference they do not follow if the RF frequency is changed. Direct digital counters remain locked to the RF signal phase when the frequency changes. However, when an absolute delay time is required, for example the time of flight thorough a transfer line, the internal reference is an advantage.

There is not much documentation available about the real precision and linearity of the delay generators. A measurement of the delay module used at KEKB indicates typical linearity of a few picoseconds and worst-case unlinearities of the magnitude of 10 picoseconds with very small delays. The jitter introduced by this module is less than 5 ps RMS at 508 MHz [16].

3.4. Flexibility

The event systems and similar provide most flexibility for operation. Because the receivers are (in most cases) individually programmable to handle the incoming events, the achievable functionality is almost unlimited. Scheduling of the software is perhaps the most convenient feature of the event systems, because this makes it possible to integrate the timing system seamlessly to the control system. Additional facilities like hardware timestamps increase the utility even further.

If the event system cannot provide enough flexibility and a separate fast timing system is needed, it is good to ensure that the two systems are compatible so that the necessary tasks can be done. For example, a feature that is unfortunately too often missing in commercial delay generators is the ability to inhibit and enable the output pulse. This is necessary for example when the fast timing is triggered from a ring revolution clock and would be used to trigger a measurement at injection or a specific turn in the ring. The fast timing delay would be disabled until the desired turn and give the output pulse only then.

The present technology allows a high performance event system to be implemented in a few field programmable logic array (FPGA) chips. The further advantage of this is that by reprogramming the FPGA, the same hardware can be modified to provide different functionality.

4 OPERATIONS

The timing system is involved in many aspects of the accelerator operation, although often not very visible (which is an indication that it is working properly). For example, the sequencing to fill a storage ring is a task which involves setting up the timing system correctly.

Top-up injection is also a task for the timing system, although not very different from the regular filling. With top-up, the heat load at experiment beamlines may be kept constant and thus the data quality can be improved [9]. The data acquisition may have to be interrupted for a while in these cases until the beam oscillations have damped. An event system or similar could do this easily, provided that the experiments are able to receive timing events.

In the accelerator diagnosis the timing system can also have a large role. An application that is planned for SLS involves a combination of the event system and a facility designed in the I/O cards. The binary and analog cards are able to autonomously record data in memory. This acquisition can be enabled and disabled with a signal. The plan is to use the event system to start and stop the acquisition on an event like a beam abort and read the buffers to to resolve the sequence that caused the beam loss.

Synchronizing magnet ramps is also a common task where the timing system is involved. With a stored beam, the ramping of magnets to steer the beam has to be done synchronously to avoid beam loss.

To support operations well, the timing system has to be well integrated into the control system. The facility with which the timing hardware can be controlled needs to be available for the control systems application developer. There are a number of approaches for the integration, and the approach somewhat depends on the hardware solution (but does not necessarily have to).

The scheduling of a storage ring fill is an example of an high-level application for the timing system. A nice scheme for sequencing is implemented at DAΦNE. The injection sequence consists of several actions, which can be put together into scripts with an editor. The timing system then executes these sequences to automatically fill the storage ring. A similar facility but with a different approach is planned for the SLS also.

The PEP-II injection system [8] has a scripting language interface, where the actions taken at each machine cycle are programmed as state descriptions and then packed into the machine scheduling codes (or events), downloaded to the timing generator and broadcast.

5 CONCLUSIONS

In spite of the variety of technologies used to implement timing systems, all the systems share many common features. Although the requirements vary according to the application of the accelerator and its parameters, the employed solutions share many common features. A form of an event system is found in most accelerators; sometimes it is applied for most of the timing, in some cases to synchronize the control software but the basic idea is the same. Most of the timing tasks could be covered by an event system with the latest technology even in electron machines.

A good integration to the control system is essential for the timing system; a well designed interface and API can enhance the operations in many ways. In view of the ever more essential software sharing between laboratories, it would be beneficial to be able to standardize the interface between timing system hardware and software like already is the case with more common devices like analog and binary input and output modules. The timing and timestamp support in EPICS from APS could serve as a good model of how this could be achieved.

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