INJECTION, RAMPING AND EXTRACTION TIMING FOR THE DUKE BOOSTER*

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Abstract

A booster synchrotron capable of ramping from 0.24 to 1.2 GeV was recently commissioned at Duke University as part of the High Intensity Gamma Source upgrade. The triggering and timing system uses a combination of software logic and triggers, digital delay generators, and hardware synchronizers to coordinate the linac injector, booster synchrotron, and electron storage ring. The injection system has been commissioned with a short pulse photo-injector linac into a single booster RF bucket and to two booster buckets separated by about half the circumference. It has also been commissioned with a long electron pulse from the injection linac into all 19 booster buckets. The extraction system, combined with short pulse kickers, can extract any of the booster's 19 electron bunches into any of the storage ring's 64 bunches. Ramping is controlled by programmable VME based waveform generators triggered from the timing system. The system offers flexibility for commissioning and operations and provides a simple interface to the operator.

INTRODUCTION

The Duke storage ring drives UV-VUV Free Electron Laser (FEL) light sources and an FEL Compton gamma source known as the High Intensity Gamma Source (HIGS). The recently commissioned Duke booster synchrotron (Table 1) was designed to provide full energy top-off injection into the Duke storage ring to support high energy gamma production. Gamma production for HIGS requires that electron bunches in the storage ring are stored in 2, 4 or 8 bunches, symmetrically spaced around the ring. The storage ring also operates in a multibunch mode for synchrotron radiation production, and in the single bunch mode for FEL lasing. Design requirements for the timing system include the ability to inject a single or multiple bunches into the booster and to extract bunches from the booster into any arbitrary fill pattern in the storage ring's 64 RF buckets. Multibunch extraction from the booster can run up to 25 Hz, the specification for the kicker systems. The booster control system needs to allow for semi-autonomous operation as an injector system. There was also the desire to incorporate a great deal of tunability into the booster's control system, on a level similar to that found in a typical storage ring control system [1].

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Table 1: Basic operational parameters of the Duke booster and storage ring.

Booster Synchrotron:	
RF Cavity Frequency:	178.5472 MHz
Harmonic Number:	19
Injection energy:	0.24–0.27 GeV
Extraction energy:	0.24–1.2 GeV
Extraction energy resolution:	1 MeV
Minimum operation cycle:	1.3 seconds
Circumference:	31.902 m
Storage Ring:	
RF Cavity Frequency:	178.5472 MHz
Harmonic Number:	64
Bunch Pattern:	any arbitrary pattern
Operation energy:	0.2–1.2 GeV
Circumference:	107.46 m

HARDWARE

For the timing system, a combination approach was chosen, utilizing a mix of software logic and triggers plus analog and digital hardware. Matching RF cavities for the storage ring and booster allows for the RF oscillator to be used as the primary timing system clock. With the relatively compact footprint of the facility, the clock can be distributed using dedicated coaxial cables. The storage ring uses an RF frequency of 178 MHz with a harmonic number of 64. For the new booster, the same RF frequency was chosen, but with a harmonic number of 19. These harmonic numbers are coprime, allowing for the extraction of any booster RF bucket into any storage ring RF bucket. Phase locked LC generators are used to produce the 2.789 and 9.397 MHz revolution frequencies for the ring and booster. These high-Q analog phase-locked oscillators are less sensitive to interference and therefore less likely to "miscount" than a digital solution [2]. The booster's 9.397 MHz clock is divided by a digital counter to produce a 1.47 kHz clock (see Fig. 1). This 1.47 kHz clock (178 MHz $\div$ 19 $\div$ 64) defines the "zero bucket," i.e. the coincidence of the booster and ring revolution frequencies. Within one period of this clock, each booster bucket will coincide with each storage ring bucket once and only once. A delay offset corresponding to an integer number of RF periods from the zero bucket can be used to match any booster bucket with any storage ring bucket for extraction.

A software derived trigger signal, synchronized with the 147 kHz clock marks the start of an injection or an extraction cycle. Because of the relatively slow injection cycle, it is feasible to incorporate an additional synchronization to the 60 Hz AC line. This helps to minimize disturbances caused by line cycle related noise sources. The synchronized injection or extraction trigger is then propagated to digital delay generators (DDG). The DDG modules provide 30 picosecond resolution, more than adequate for our sub-nanosecond requirements. The DDG delays can be dynamically programmed during the injection or extraction cycle to step between buckets. For ramping, a synchronizer is used to match the trigger signal to the 60 Hz line to match any power supply ripples. The synchronized trigger is then split and distributed to waveform generator boards. Each channel of the waveform generators, which can also be reprogrammed during operation, drives a ramping power supply.

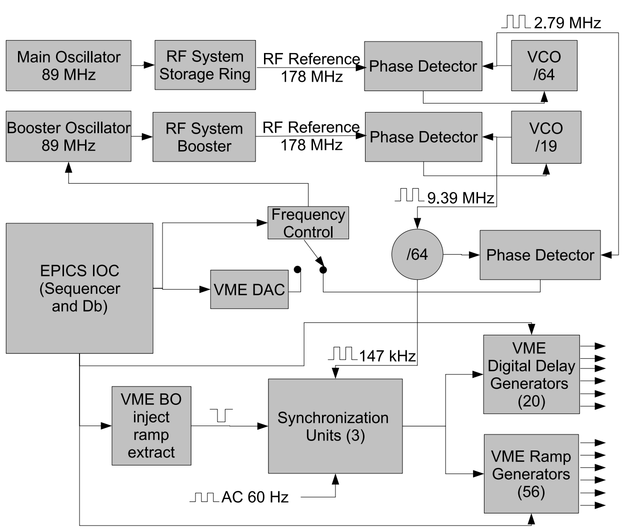

Figure 1: Block diagram of the timing system.

SOFTWARE

Software controls for the timing system are distributed to EPICS input/output controllers (IOC) so as to minimize network traffic. The IOCs run a realtime operating system, and are used for millisecond level timing. The injection / ramping / extraction cycle is driven by a sequencer program. States for injection, ramping, extraction and normalization are handled by the sequencer, providing logic for any operation or testing mode. Simple operator controls allow the linac injection, booster ramping, and booster extraction to be run individually or in step-by-step mode for testing or tuning, or to be run continuously in an automatic manner for filling the storage ring or to maintain the storage ring current at a set value during top-off operation.

For injection, any combination of booster buckets can be selected in the photoinjection mode. With the injection kicker pulse length of about 100 nsec, a single bucket or two buckets (separated by approximately 50 nanoseconds), can be stored. The gun laser currently in use has a pulse length of 1–2 nsec, short enough to fill a single 5.6 nsec RF bucket. Based on the chosen bunch pattern, the injection DDG modules are programmed to delay the laser pulse relative to the zero bucket to inject into the selected buckets. The software also supports a multibunch injection for a long pulse electron train from the linac.

The ramping cycle is triggered after a setable delay to provide sufficient damping time for the stored beam. High level control for all ramping power supplies is in terms of the effective focusing strength of the magnets [3]. Changing booster injection energy (to match linac energy) or extraction energy (to match storage ring energy) reprograms the ramping waveform generators for all power supplies with the appropriate ramping curve with start and stop points matching the target energies. At the end of the energy ramp, an interrupt is generated which begins the extraction process. After extraction, the ramping continues to maximum energy (1.2 GeV) and then back to injection energy, completing a magnet normalization cycle.

For the extraction process, an array of the booster buckets filled during injection is matched with an array of the ring buckets targeted for filling. Ring buckets are filled sequentially, through multiple ramp cycles if the number of ring buckets selected is greater than the number of booster bunches filled. Each booster bunch is extracted individually to a single ring bucket. This is made possible by using an extraction kicker with a flat top of only 4 nsec. A table of the calculated integer number of RF periods of delay for the buckets to coincide is used to set the DDG modules during the extraction process. This system can run at greater than 100 Hz, but is limited by the kicker system to 25 Hz.

Additionally, diagnostics are gated with the injection cycle. Using the beam current monitor on the booster, a peak sensing charge calculation records the charge stored per cycle in the booster. Likewise, a beam current monitor on the storage ring is used to calculate the change in charge per cycle which can then be used for determining the efficiency of booster injection into the storage ring.

PERFORMANCE

The timing system has been in operation and has met all requirements. In addition, it has proven to be flexible enough to meet a few unanticipated needs.

Initial commissioning and operation utilized a laser driven photoinjector gun for the linac system. A single bunch was injected into the booster in each cycle. However, during commissioning, the drive laser suffered a catastrophic failure. To continue commissioning, a pseudo-thermionic mode was used with a long electron pulse of low charge. The booster injection kicker, with a 100 nsec pulse, was able to fill all 19 of the booster buckets in a single cycle, with charge in each bunch of only a few pico coulombs. A mode was added to the timing system to support the 19-bunch multibunch injection. Bunch-by-bunch extraction of all 19 booster buckets at rates up to 25 Hz was demonstrated.

After a replacement gun drive laser was installed, commissioning continued with photoinjection. To increase total booster current, two bunch booster injection was attempted. The injection kicker's pulse length of 100 nsec was designed to match the booster revolution period of 106.4 nsec. However, the rising and falling edges of the pulse have a slight asymmetry. By adjusting the timing delay for the kicker relative to the gun laser, it is possible to inject into bucket ten without disturbing the charge already stored in bucket zero. The second bucket is separated from the first bucket by 56.0 nsec on one side and 50.4 nsec on the other side so the first bucket only sees part of the shoulder of the kicker pulse. Although this was not part of the initial design, it provided a simple way to nearly double the charge per cycle in the booster, while adding less then 70% to the cycle time.

The system was initially designed for injection at 270 MeV with extraction over the range of 270 to 1200 MeV. Extraction has been demonstrated over the full range of 240 MeV to 1200 MeV and injection from 230 MeV to 275 MeV. The lower energy operation was necessitated by linac performance. The booster systems proved to be flexible enough to easily change injection energy. In practice, it is generally quicker and easier to adjust the booster injection energy to match the linac energy then it is to optimize the linac energy to its nominal value.

CONCLUSION

This timing system fits into our approach to develop a "virtual accelerator" using standard control system tools. The virtual accelerator provides a high-level interface in the terms of the accelerator physics of the machine rather then in the terms of the engineering implementation. The timing system is a highly tunable subsystem of this virtual accelerator. Damping time for the electron beam at different energies is easily adjustable. Additionally, the timing system provides an intuitive approach to RF bucket fill patterns, simplifying operations and accelerator physics research such as beam instability studies. Currently, we are only able to measure the total charge stored in the storage ring. This allows automated top-off injection, but does not allow precise control of charge per bucket in multi-bucket modes. Additional diagnostics, however, could provide bunch-by-bunch charge measurements to the timing system. This would ensure consistent fill patterns and simplify the study of multibunch interactions by allowing automatic top-off for each bucket to an independent charge set point.

With a more typical, low-level hardware approach to timing systems, tuning and adjusting the ramp cycle is limited. By adding a level of software control to the timing system, a great deal of flexibility is added. Full control of the ramping cycle is available at each step, allowing injection, ramping and extraction to be run independently. Software delays can easily be added to various points in the cycle including after injection, after ramping, and between multiple buckets of extraction to observe beam conditions. In addition, the ramping cycle can be stepped through to allow measurement and tuning of the booster during the entire energy ramp.

This has made the low cost, very compact booster more of a possibility. Commissioning was simplified and sped-up by this flexibility. The ability to tune the ramping waveforms using stored beam provided a means to compensate tunes and chromaticity shifts from the highly saturated magnets.

The overall approach has resulted in a timing system which offers a great deal of flexibility. The approach should prove useful for other compact boosters operating at a few Hz or less. At higher repetition rates, the transient effects will limit the usefulness of steady-state tuning and measurements. For the Duke booster, operating at less than 1 Hz, all initial design requirements have been met and additional operation modes have been explored.

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