SNS Timing and Synchronization System

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SUMMARY

This Technical Note reviews and summarizes the status of the SNS timing and synchronization system conceptual design as of the recent Timing and Synchronization Workshop, held at Brookhaven National Laboratory on May 3-5, 1999. This is the first such workshop after the meeting held at Los Alamos National Laboratory in January 1998. Subsequent to that meeting, several reports were written, including a summary and conclusions of that workshop, and Technical Notes addressing certain specific topics related to the SNS timing and synchronization requirements.

This Technical Note, as are the previous ones, is based on the Linac-Accumulator Ring (LAR) baseline design. Some of the details presented here are specific to the LAR concept, and would have to be modified if a Rapid-Cycling Synchrotron (RCS) design were adopted for SNS. Although more difficult, the timing and synchronization system concept presented here can be adopted for either baseline design.

The workshop at Brookhaven focused on the system used for distribution of timing signals to systems such as the beam chopper system in the linac injector, and to beam diagnostics systems around the ring, and along the linac and beamlines. The preference was to adopt a single site-wide, beam-synchronous (with the beam in the ring) timing system, that broadcast encoded timing signals on a clock signal that was an exact harmonic of the ring revolution frequency. It is very likely that the beam-sync timing system developed for RHIC can be used for SNS with at most minor modifications.

INTRODUCTION

The primary purpose of the sitewide SNS synchronization and timing system is threefold:

1) Synchronize the Fermi neutron (velocity-selecting) choppers to the zero-crossing of the 60-Hz line power;

2) Synchronize the extraction of the accumulator ring to the Fermi neutron choppers;

3) Distribute appropriate timing signals to various accelerator systems (including the Injector, the Linac, and the Accumulator Ring) in order do accomplish items 1 and 2 above.

This document reviews the synchronization requirements needed for synchronizing the neutron choppers, the ac line zero crossing, and the ring extraction kickers. This document also reviews the requirements for the timing signal distribution system.

NEUTRON CHOPPER TO AC-LINE SYNCHRONIZATION

The neutron choppers are very high inertia mechanical rotors with collimators that chop the neutron beam, rotating at a high harmonic of the line frequency, probably (but not always) at 600 Hz. There are several such choppers, but one will be used as the reference for the others. The frequency and phase of the reference neutron chopper will be phase-locked to a line reference (“line-sync”) signal, which in turn is phase-locked to the ac line zero crossing. The desired timing accuracy for the synchronization of the neutron chopper to the line-sync signal is about ± 0.5 µs. The required accuracy is still to be determined, but is in the ± 1-µs range. Present systems in use at LANSCE and at IPNS achieve timing accuracy in the range of ±10 µs, but are believed to be upgradeable to the ±1-µs range.

The ac line-sync signal will be phase-locked to the average line zero-crossing signal using digital signal processing (DSP) techniques. DSP processing is preferable to analog processing due to the very long time constants involved.

The ac-line synchronization requirement is to maintain a timing accuracy of about ± 500 µs or better between the zero crossing and the line-sync signal, even during line frequency transients and diurnal variations. This requirement stems from the need to synchronize the linac klystron modulator pulses to the ac line zero crossing in order to have pulse-to-pulse repeatability in the klystron performance.

Measurements on the line frequency variations indicate that the 60-Hz line frequency can deviate by as much as ± 0.2 Hz (3300 ppm) from the nominal 60-Hz frequency, and this variation can occur in periods of 10 minutes or less. The line-sync phase locked loop must track this frequency change, while maintaining the ± 500 µs timing accuracy, and accomplish this with frequency slewing rates not exceeding about 0.2 Hz in 500 seconds (about 6 ppm frequency shift per sec). This latter requirement is due to the very high mechanical inertia and “Q” of the neutron chopper systems.

In order to synchronize the accelerator systems to the DSP line-sync circuit and the neutron chopper PLL, a phase-stable timing signal, probably at 600 ± 2 Hz, is generated and distributed around the facility. This 600-Hz signal can be encoded on the beam-sync timing system. The specific reason for this frequency choice will be discussed later.

A conceptual block diagram of this system is shown in Figure 1.

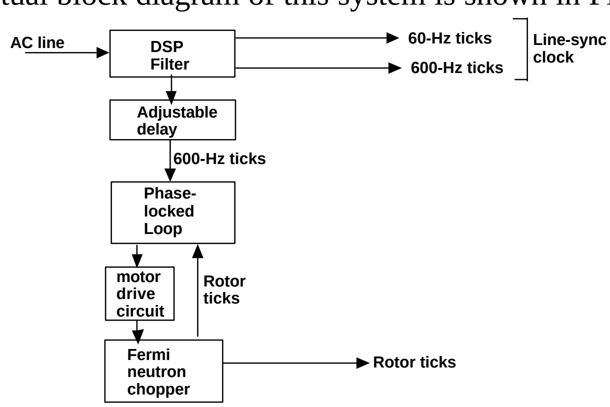

Figure 1. Conceptual block diagram of the line and neutron chopper rotor synchronization circuits.

SYNCHRONIZATION OF RING EXTRACTION TO NEUTRON CHOPPER

The ring revolution frequency is about 1.19 MHz ± 0.2%, corresponding to a period of about 841.2 ± 2 ns. The beam occupies about 67% of the ring circumference, and the remainder of the ring (the beam gap) is free of beam (to about 1 part in 10^5) in order to accommodate "clean" extraction (without unnecessary beam loss). The extraction from the ring must be synchronized to the beam to about ± 5 ns (the beam gap is about 280 ns long). Because the synchronization requirement for the ring extraction to the neutron chopper is longer than 1 ring revolution period, the phase of the beam in the ring does not need to be synchronized to the neutron chopper prior to extraction. The neutron chopper system need only provide a 1000-ns gate signal during which the ring extraction kicker is triggered when the beam gap at the correct azimuth. The circuitry for generating the 1000-ns gate, and synchronizing the neutron choppers to it, is the responsibility of the group developing the neutron choppers.

SYNCHRONIZATION OF LINAC

In order to inject approximately 1160 turns into the ring, the beam injection into the linac must begin about 975 μs before extraction. For a normal-conducting linac, the klystron modulators must be pulsed about 100 μs earlier than the beam (For a superconducting linac, the lead time is 300 or 400 μs). The reason for this is to fill the rf cavities with field before the injection of beam. For a superconducting linac, there is also the issue of mechanical transients in the rf cavities caused by Lorentz forces. Thus the first required timing pulse for a complete beam pulse cycle is required about 1500 μs before the ring extraction time.

When the ring is full at the end of accumulation, the beam is very close to being unstable, and the beam must be extracted within a few μs (say <10 μs) after the last turn is injected. If the accelerator cycle timing start signal T_0 is based on 60-Hz line-sync signal, which has a period of 16,667 ± 50 μs (due to line frequency variations), the variation in the delay between the cycle start signal T_0 and the extraction time exceeds the allowed storage time in the ring. By using the 10^{th} harmonic of the line frequency, 600 Hz (which has a period of 1667 ± 5 μs) as the source for T_0, the critical systems in the linac (modulators, injector, etc) can be triggered with a timing error not exceeding the allowed 10 μs "window" relative to the extraction time. This will be shown in Fig. 2.

RING REVOLUTION PERIOD

Choice of Revolution Period

The ring revolution period for a 1-GeV proton circulating in the Accumulator Ring (circumference 220.667 meters) is 841.194 ns. This is the 338.58^{th} harmonic of the linac RF (beam bunching) period of 2.484 ns. This harmonic number was specifically chosen to be a non-integer in order to minimize space-charge effects in the ring during accumulation. The ring period may vary by as much as ±2 ns, depending on the exact beam energy and closed orbit.

Determination of Ring Revolution Period

The ring revolution period is determined by *coasting* a single turn (a 500-ns long beam pulse) for many turns without any applied RF power, and measuring the "natural" period.

On subsequent beam accumulation cycles, the ring RF frequency reference will be based on the measured natural frequency (because of beam loading in the RF cavities, there is a phase shift of nearly 90 degrees during accumulation). Thus the ring revolution period is based on the natural revolution period of the beam in the Accumulator Ring, and not on the linac RF frequency, as is the case for the Proton Storage Ring (PSR) at Los Alamos.

Variation in the Ring Revolution Period

For a 1-GeV proton circulating in a ring of circumference 220.667 meters, the revolution period is 841.194 ns. During normal operation, tuning the ring by changing the B field (which changes the orbit radius), or tuning the linac to change the injection energy, or a combination of both, can change the revolution period by up to ± 2 ns. During ring commissioning, the change can in principle be even larger. Although 2 ns is not a large number, the cumulative timing error over a normal accumulation cycle of 1200 turns exceeds 2 µs, more than one complete ring period. This is much larger than the desired cumulative synchronization accuracy of ± 5 ns for accumulating 1200 turns of beam in the ring. Any cumulative error exceeding 10 ns can begin to fill in the beam gap in the ring. Any beam in the gap will activate the extraction septum.

Figure 2 shows the overall 16.667 ms timing cycle for beam accumulation in the ring. Figure 3 shows a detail of the 1.667 ms period beginning with the cycle T_0 pulse. The T_0 pulse is every 10th tick of the 600-Hz line-sync signal shown in Fig. 1. In both Fig. 2 and 3, T_{ext} (ring extraction time) is one 600-Hz period later. This should be synchronous with the 1000-ns gate from the neutron chopper PLL.

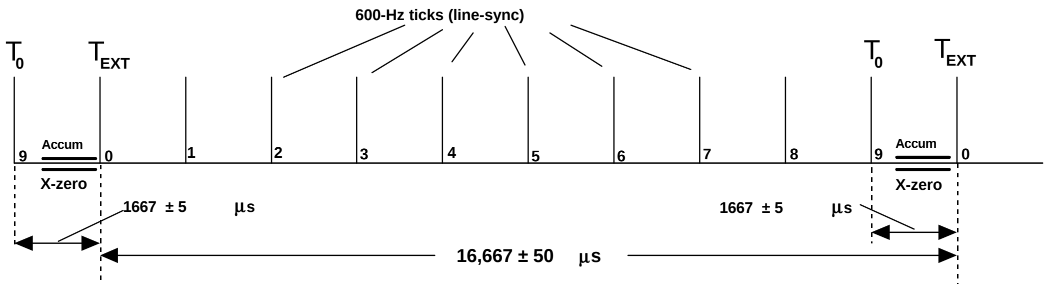

Figure 2. Overview of the timing for a 16.667-ms beam pulse cycle. T_0 is the start of the accumulation cycle, and T_{ext} is the ring extraction time. The 60-Hz clock can vary by up to ±50 µs due to line frequency variations, but the 600-Hz clock can vary by only ±5 µs.

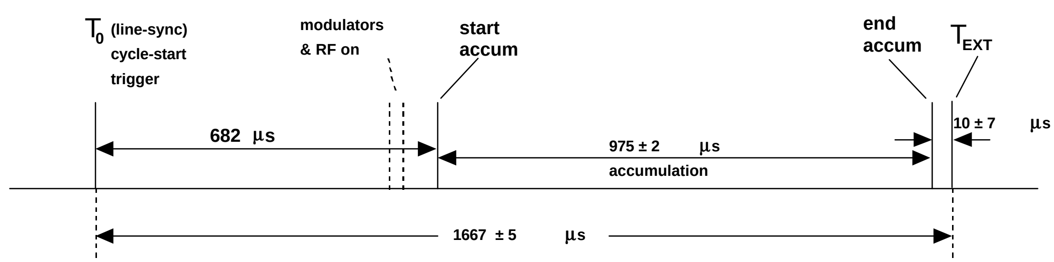

Figure 3. Detail of the 1.667-ms accumulation cycle. Beam accumulation begins about 682 µs after T_0. Accumulation requires 1160 turns, corresponding to about 975 µs. Approximately 10 µs after the end of accumulation, the beam is extracted from the ring when the extraction trigger signal T_{ext} is received from the neutron chopper circuit in Fig. 1. The 10-µs delay between the end

of accumulation and extraction is required due to variations in the line frequency and in the accumulation time.

LINAC BEAM CHOPPER SYNCHRONIZATION

The beam in the linac injector is chopped by three systems, including a gated H^- ion source, gated electrostatic focusing electrodes in the LEBT, and a traveling-wave deflector (beam chopper) in the MEBT following the RFQ. Each of these systems, and especially the beam chopper in the MEBT, must be synchronized to the ring period. The reason for the chopping is to produce a gap in the beam current, about 280 ns long, that is synchronized to the ring period with a cumulative error of about ± 5 ns for the entire 1200-μs accumulation period.

This approach is different from the beam chopper system used for injection into the Los Alamos proton Storage Ring (PSR), which runs at an exact integer harmonic (72) of the linac RF period. The PSR ring period is then set to match the beam chopper period. Although the Los Alamos system is easier to implement, it forces the ring period to be an integer harmonic of the linac beam bunching frequency. This leads to possible space-charge effects that are avoided by using non-integer period ratios.

With a non-harmonic period ratio (338.58 to1) of the SNS beam chopper and the linac (RFQ) rf frequency of 402.5 MHz, there has been some concern about the beam dynamics of partially chopped microbunches in the linac. This led to chopper risetime requirements of the order of 3 ns, and for deskewing circuits to synchronize the chopper rise and fall times to the beam microstructure (this would be done using a D-type flip-flop clocked at 402.5 MHz). Recent beam dynamics simulations show that partially chopped bunches are not a concern, and the chopper risetime and falltime can be 5 ns or more. Thus a deskewing circuit is no longer required.

BEAM DIAGNOSTICS SYNCHRONIZATION

Ring Diagnostics

The beam diagnostics in the ring measures the evolution of the beam “sausage” during the 1200-turn accumulation cycle. The ring beam diagnostics measurements include *global* systems such as beam closed orbit measurement (BPM) system, and *local* systems such as the azimuthal distribution of beam charge density (current monitor). *Global* and *local* refer respectively to systems that are widely distributed around the ring, or needed in only one or two azimuthal locations. These systems need to be synchronized to the beam in the ring to within about ±5 ns, even though the 975-μs accumulation period may vary by 1200 ns or more.

Linac Diagnostics

Even though the linac RF is not synchronized to the ring (or vice versa), the periodic beam gap in the linac is. Because of the effect of the beam gap on the performance of the linac beam diagnostics, the sampling of the beam diagnostics signals from all the diagnostics needs to be synchronized relative to the beam gap in order to minimize transient effects. In particular, beam current, beam position, and beam synchronous phase measurements would benefit from being synchronized relative to the beam gap. Thus the linac diagnostics also needs to be synchronized to the beam in the ring. Although the beam chopper frequency is well above the control bandwidth of the RF power systems, there may be some use in having a real-time signal synchronous with the beam gap for RF feed-forward applications. In the case of linac beam diagnostic systems, a 50-ns timing *granularity* (not *jitter*) of a timing signal relative to the beam gap is adequate (the beam gap is 280 ns long, and the beam minipulse between beam gaps is 560 ns long).

In the case of the linac, a signal travelling along the linac with the beam from the injector at b = 0.6 the speed of light will beat the beam to the end (for a 460-m linac, the beam transit time is about 2725 ns, and the signal transit time is about 2557 ns). Thus it would not be difficult to distribute a beam-gap-synchronous signal along the entire linac using fiber optics. Such a signal would be made available to any system requiring synchronization relative to the beam chopper gap.

Beam lines

Diagnostics in the beamline between the linac and ring requires synchronization to the ring period. In addition, RF cavities in this beamline require the 805-MHz reference signal. Diagnostics in the beamline between the ring and the spallation target need only a single pretrigger a few 100 ns before extraction.

REQUIREMENTS FOR A SITE-WIDE TIMING SIGNAL DISTRIBUTION SYSTEM

We can now summarize the requirements for a site-wide timing signal distribution system, based on the above discussion. This is a system with a single transmitter, and many 100's of clients (receivers) distributed along every beamline as well as in the experimental areas.

Timing stability. About ± 5 ns (relative to the beam in the ring). This includes long-term drift and pulse-to-pulse *jitter*. Stability in this range allows use of the timing system for triggering the beam chopper in the linac injector and the extraction kicker in the ring, as well as for all the beam diagnostics. The timing system described here does not need to address the timing (phase) stability of the linac rf systems, which must be stable to ±0.5 degrees at 805 MHz (about ± 0.002 ns). *Granularity* is discussed later.

Frequency compliance (to variations in ring revolution frequency). Many systems in the injector, linac, and ring, will have individual downloaded delay settings (integer cycles of a reference clock). Variations of the ring revolution period up to ± 2 ns (± 2400 ns for a complete accumulation period) should not require changing any downloaded preset delay settings in order to maintain the 5 ns timing stability relative to the beam in the ring.

Clock. The distributed clock signal must be CW, independent of whether beam is in the ring.

Clock reset. Periodic clock resets must be distributed to synchronize all receivers. The number of clock periods between resets should not exceed 2^{32} (about 200 s for a 20-MHz clock).

Real-time event encoding. Ability to encode and transmit 100's of distinct timing signals ("events") in a real-time fashion (meaning synchronized to a clock). An event prioritizing system is required to ensure that important timing signals are transmitted on the correct clock cycle. Real-time events include all the preset timing signals, such as for beam choppers, klystron modulators, etc. In addition, triggers are required for synchronizing beam diagnostics measurements (beam position and beam synchronous phase measurements in the linac, closed orbit measurement in the ring, and pretriggers are required for the diagnostics in the ring-to-target beamline).

Number of distinct event (trigger) types. This refers to the "vocabulary" of the timing system. Certainly not more than 1024, very likely less than 256. This needs further discussion.

Granularity. 50 ns is adequate. This refers to the timing system clock period, which should be short relative to the ring period. This relates to the minimum step size in setting the transmission time of encoded events. Finer delay settings can be achieved by using fixed length cables, or by using delay chips that are remotely programmable with better than 5-ns delay granularity and stability. *Granularity* does not need to be as good as *timing stability* (see above).

Transmission method. *Broadcast* transmission over optical fibers or cables, rather than *point-to-point* transmission. *Broadcast* means the signal is received by *all* listeners, while *point-to-point* means the signal is received by a *single* listener. The simplest approach would be to use a self-clocking link in which the timing signals are encoded on the clock signal. The timing system has a single transmitter, and hundreds of receivers (listeners). The receivers each recover the original unmodulated clock signal (carrier), and have individually programmed digital filters to recognize and decode specific encoded "events".

Distribution mechanism. Encoded event (trigger) signals and clock are on same fiber (or cable) to permit convenient distribution over the entire site. Use of separate fibers for clock and for timing signals (such as reset) often leads to timing ambiguities because of fiber length differences or thermal effects.

Distribution area. Sitewide. Preference was shown at the BNL workshop for a single sitewide timing system rather than several local systems; e.g., one for the ring and another for the linac. This means that *all* receivers will receive *all* transmitted events, including linac-specific and ring-specific events.

Bit error rate (BER). Whatever it has to be to ensure an acceptable reliability.

Informational events. The timing system should have the ability to distribute *informational* events as well as *timing* events. *Informational* events might include identifying the accelerator cycle type (e. g., beam to spallation target or to linac beam dump, or Beam Pulse Disable (e.g., ring extraction kicker capacitor bank not completely charged by time T_0). The critical timing signals occur in the 1.67 ms between T_0 and T_{ext}

(see Fig. 3). There is 15 ms between T_{ext} and the next T_0 signal, and about 600 μs after T_0 for informational events. Informational events can be transmitted with a lower priority than (can be “bumped” by) timing events because their exact timing is not critical.

Priority system for event transmission. Critical timing events are given priority for a given time slot to prevent any contention. Non-critical timing signals are delayed (by about 1 μs (a 12-bit word requires about 12 clock cycles or 630 ns to transmit). Informational events have a low (low-time-critical) priority.

Time stamp. This timing system is not intended to replace the need for the normal time stamp requirement. The time stamp must be accurate enough to uniquely identify individual 60-Hz beam pulses. The function of the timing system is to synchronize systems to a few ns within individual beam pulses.

CONCEPTUAL REALIZATION OF BEAM-SYNC CLOCK

The most convenient way to *broadcast* timing signals to many hundreds of clients distributed over nearly a kilometer of accelerator and beamlines is to encode all the timing signals on a carrier frequency (clock), and to distribute this signal to *all* clients. Putting the timing signals on the same cable (or fiber) as the clock eliminates the possible timing ambiguity due to non-equal cable lengths. Use of encoding techniques, such as biphase encoding (e.g., Manchester codes), allows the transmission of up to 256 different 8-bit codes in a 12-bit word. With the Manchester code, this word requires 12 clock cycles. Each client has a receiver that decodes the 8-bit timing signals and recovers the carrier (clock) frequency. Digital filters in each client (receiver) are programmed to recognize specific real-time trigger signals, which are synchronous with the clock cycles.

If the clock frequency is a fixed frequency, then making the timing system compliant to normal day-to-day variations in the ring revolution period very difficult. It would require downloading new time delays using point-to-point (channel access) communication to every client whenever the ring period changed by more than a few ps.

If the clock frequency is synchronous with the beam in the ring, then any time delay based on counting clock cycles remains synchronous with the beam, even though the total ring 975-μs accumulation period may vary by as much as ±2 μs. Discussion of possible “beam-sync” clock frequencies at the BNL workshop led to recommending the 16^{th} harmonic of the ring frequency, 19.02 MHz, as the most likely candidate. Because it is the 16^{th} harmonic of the ring frequency, generating the 1.188-MHz ring revolution clock ticks is straight forward. Existing beam-sync systems at Fermilab (Tevatron) and Brookhaven (RHIC) use 10 MHz and 14 MHz clocks respectively. In the case of RHIC, there are two beam-sync clocks (yellow and blue), one for each ring. 19 MHz was believed to be easily achievable for an SNS beam synchronous clock.

The frequency swing in the RHIC beam-sync system is of the order of 0.5%, a requirement due to the non-relativistic nature of gold atoms during acceleration in the RHIC ring. This exceeds the frequency swing requirement (±0.2%) in the SNS Linac-

Accumulator Ring (LAR) baseline design. The Rapid Cycling Synchrotron (RCS) design would require about a 15% frequency change in a few ms.

The bench measurements of the RHIC beam-sync system indicate that the bit-error rate is of the order of 10^{-11} (using copper cable). The SNS Controls Group needs to determine whether this BER is acceptable for the SNS application.

CONCLUSION

Several Laboratories are developing systems to achieve the required 1-μs timing accuracy between neutron choppers and a line-sync signal tracking the 60-Hz zero crossing. Achieving 1-μs synchronization between the neutron choppers and the ring extraction is straightforward. Sitewide distribution of timing signals with 5-ns stability with a ring-frequency-compliant beam-sync timing system is possible using existing equipment developed for RHIC with only minor modification.