SNS Timing Workshop Summary

(Rev 2/20)

Bob Shafer and Dave Gurd

A Timing Workshop to review the SNS accelerator system timing and synchronization requirements was held at Los Alamos on January 26, 1998. This document is an attempt to summarize the workshop discussions and issues. It is not a design document. Transparencies shown during the workshop have already been distributed to participants.

The primary focus of the Workshop was to discuss issues related to the neutron (Fermi and T_0) choppers, the accumulator ring rf frequency, phase and extraction time, the linac rf, the MEBT beam chopper, and whether to synchronize any or all the above to the 60-Hz line frequency.

The specific goals for this Workshop, as outlined by Jose Alonso, were to work toward

1) Developing a functional specification that would provide for high efficiency operation (low pulse rejection rate), and
2) Developing a design strategy for the SNS timing and synchronization system.

One important goal of this meeting was for the participants to reach a common understanding of how various timing signals and systems throughout the facility relate to each other, and how various requirements, such as synchronization of beam pulses on the spallation target to the neutron choppers and synchronization of the linac macropulse to the line frequency, impact the overall timing system. In addition, the workshop allowed collaborators representing the ion source, linac, ring, spallation target, and users to better understand how their own timing requirements impacted other systems. Lastly, the workshop helped identify whether there were serious technical problems in achieving the overall timing requirements, and whether possible solutions existed.

This workshop summary is organized according to the discussion topics below:

- <u>Line synchronization</u>
  - Are equal-spaced beam pulses during multiple target operation needed?
  - Will users accept line-synchronous operation?
  - Charging time for modulators and pulse forming networks (PFNs)
  - Klystron gun sensitivity to ac phase
  - Zero-crossing trigger circuits
    - line noise
    - narrow band passive filters
    - (Phase locked loop (PLL) active filters
  - Line frequency variations
    - tracking the variations

Neutron choppers
- T_0 and Fermi choppers
- Synchronization of all choppers to each other

Ring extraction
- Synchronization to beam gap and to neutron choppers

Ring RF
- Synchronization to linac rf, or is it independent of linac rf?
- Determination of ring rf phase; is it necessary?

Beam chopper in MEBT
- Synchronization to ring rf, or synchronization to linac rf
- De-skewing requirement (synchronization to 402.5 MHz)
- Beam current ramp-up at beginning of macropulse

Linac RF
- 402.5 and 805 MHz to RFQ, DTL, CCDTL, and CCL
- 805 MHz to beam bunch rotator in linac-to-ring transport .

Macropulse sequencing
- Beam pulse permit
- Beam precursor pulse requirements
- Relationship to Run Permit and Fast Protect.

Figure 1 shows a possible overall architecture for the SNS timing system. This diagram should not be considered as a proposed design for SNS. Rather it is presented here to help clarify the discussion which follows. The diagram shows timing signals for the linac and the ring extraction being derived from the ac line and from the neutron choppers. It also shows the beam choppers in the injector and the ring rf - both operating from an independent rf source.

Line Synchronization Issues

The first issue discussed was whether or not the users (neutron scatterers) require equal-spaced beam pulses, even when the facility is providing 50 pulses/sec to one target and 10 pulses/sec to another. If the 50 Hz pulsing occurred with a 20 ms pulse spacing, and the 10 Hz at a 100 ms spacing, the pulse intervals would have to vary between 10 and 20 ms, and could not be synchronized to the line (16.667 ms period). Kent Crawford indicated that although equal-spaced 50 Hz pulses would be preferable, unequal spacing of the 50 Hz pulsing ("pulse stealing" mode) would be acceptable. This permits line-sync operation of the linac. In this mode, every fifth 50 Hz pulse is spaced at 33.33 ms, the rest being spaced at 16.67 ms. See pages 7 and 8 in Alonso's presentation for illustration.

Line-sync operation of the linac is preferred for several reasons. It permits equal-spaced linac pulses, all with a pulse spacing of 16.67 ms, thus maximizing the time allowed to charge PFNs and capacitor banks. For 50 Hz /10 Hz operation in the "equal-spaced" mode, the charging time would be either 10 or 20 ms, interleaved. This would require higher peak voltages and currents in the charging supplies than in the "pulse-stealing" mode.

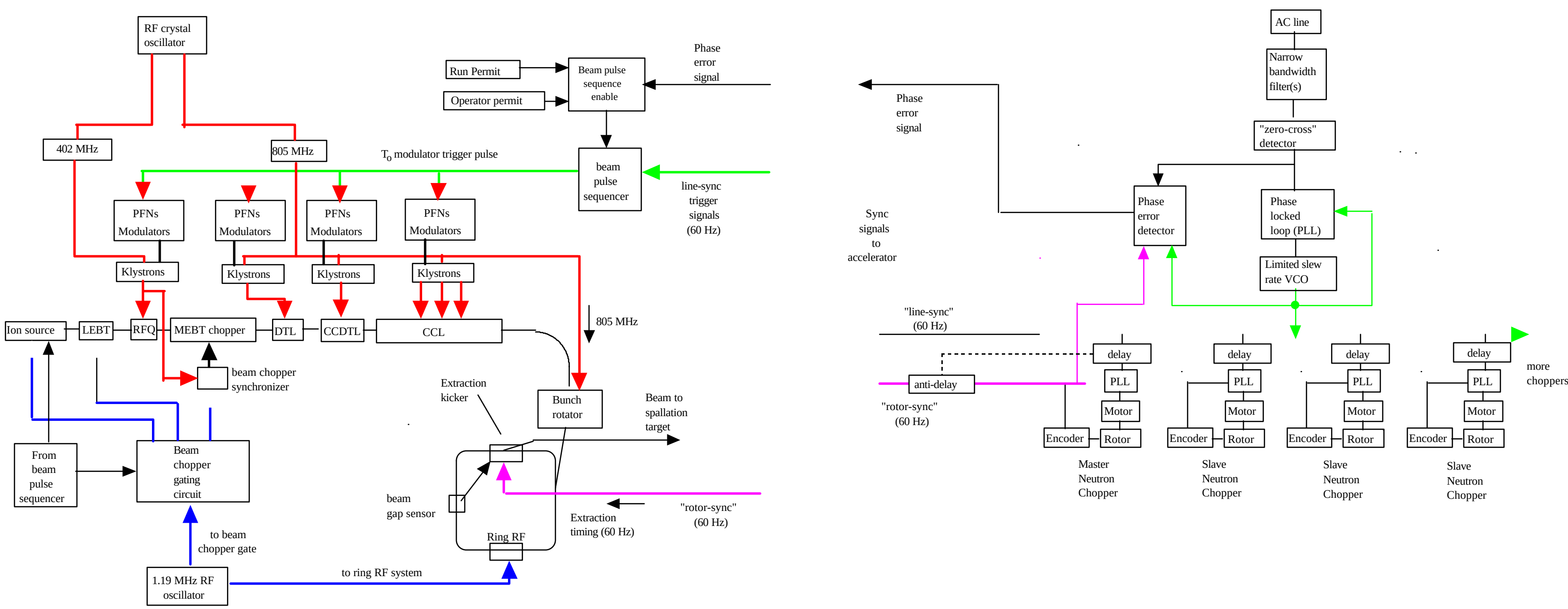

Figure 1. Possible timing architecture for reference and clarification of discussion.

Secondly, achieving peak power in the klystron depends on the phase of the 60-Hz ac filament current, because the beam optics in the klystron gun depend on the magnetic field from the current in the filament. A dc supply (about 800 watts of filament power) could be used here, but the supply would have to float at about – 80 kV, the cathode potential. In addition, adding a dc supply here will impact the klystron power supply reliability. See discussion in Mike Lynch's presentation.

To produce a line-synced timing signal, a 60-Hz "zero-crossing" signal is generated when the filtered line voltage changes polarity. The exact timing of the zero-crossing line-sync pulses is very sensitive to noise and distortion on the ac line. In order to achieve a line-sync trigger signal with minimum jitter, the line signal could be processed through a combination of passive (Butterworth) and active (analog or digital phase-locked loops) circuits to generate a line-sync signal that is sufficiently free of timing jitter. This has been done both at LAMPF and at IPNS with generally satisfactory results. Neither of these facilities were originally designed for the tight synchronization requirements needed for the neutron choppers, so SNS should easily surpass the performance already achieved at other facilities. An alternative to analog filters could be to digitize the line waveform and predict zero crossings.

Because of hour-by-hour (or faster) line-frequency variations (typically ± 0.01 Hz observed at ORNL; see Jose March-Leuba's presentation), the line-sync trigger circuit must track these variations, but slowly enough so that the high-inertia neutron choppers, which rotate at harmonics (up to 600 Hz) of the linac pulsing frequency can also track these variations. Furthermore, because there will be many neutron choppers, including at least two Fermi choppers, they must be slaved to a master chopper.

Neutron Choppers

There are two types of choppers, the T-zero (slow) choppers, generally rotating at 3600 rpm (60 Hz), and the Fermi (fast) choppers, rotating at synchronous speeds of up to 36,000 rpm (600 Hz). The slow choppers are primarily to prevent fast neutrons from reaching the detectors, and mitigating frame overlap. The fast choppers, located many meters away from the spallation target, have a timing window requirement of about 1 to 2 μs relative to the beam pulse for narrow-band neutron velocity selection.

Optically-coupled angular phase encoders on the chopper rotor, in combination with phase locked loops (PLLs), have been used to synchronize multiple neutron choppers to within about 1.1 μs, and to a master clock (such as the line clock) to about 4 μs (Lawrence Donley, ANL). Some of the timing jitter in the neutron choppers is due to the bearing design (mechanical vs. magnetic) and not to the control circuitry. (Note: Good PLL circuits (e.g. Motorola MC14046B) using type 2 (sequential) phase comparators have achieved phase locking accuracy better than 100 ns on 500-Hz signals in high-Q electrical circuits. Type 1 (analog) phase comparators have much better noise immunity, but poorer phase-locking accuracy. The MC14046B has both types on the same chip.)

For multiple neutron choppers, the master clock signal to which all neutron choppers are synchronized could be used to control the ring extraction time, provided the neutron choppers track it with sufficient accuracy. Otherwise, the extraction signal would have to be derived from a master chopper rotor.

It would certainly be simpler to derive a ring extraction gate signal from the ac line, via filters and phase locked loops to limit the slewing and triggering jitter, but to do this may require some development. At present, direct ac-line triggering results in an excessive number of pulses with excessive timing errors relative to the chopper rotor signal. Another difficulty with using the rotor as a phase reference is that the Fermi chopper phase delay relative to the beam pulse must be variable relative to the extracted beam pulse, in order to select neutrons of different energies. This delay must be removed from the beam extraction gate, if it is derived from the rotor and not the ac line. In concept at least, it should be possible, using digital signal processing, to electrically generate the same response as a mechanical system with high rotational inertia.

It was mentioned (by John Sandoval) that at the Manual Lujan Center (LANSCE) it takes several hours to set up the neutron chopper synchronization prior to beginning scattering measurements. There is possibly some room here for developing an automated system for setting and controlling the neutron chopper phase accuracy and stability.

The experience at LANSCE, LAMPF and IPNS is valuable in identifying problem areas and in suggesting areas for development in line synchronization and neutron chopper phase control that can be used in designing the SNS ring extraction triggering system.

Ring Extraction Time Synchronization

Ring extraction needs to be synchronized to the neutron chopper master clock (or rotor) with an accuracy of about 1 to 2 μs. Better timing is not required, due in part to the neutron thermalization time in the spallation neutron target moderators, and to the chopper collimator time window itself. This implies that the beam gap in the ring may be asynchronous relative to the neutron chopper, because the ring period is 841 ns, and at least one complete beam gap in the ring (280 ns) will always be within a 1.2-μs-wide neutron chopper gate signal. It was suggested that if necessary, the beam pulse timing within the neutron chopper gate could be digitized and used for correcting experimental data, pulse by pulse. At present, beam gap synchronization to better than the neutron chopper timing gate width is not needed (Kent Crawford).

Ring RF synchronization

There are two schools of thought here, and the workshop did not reach full agreement on a preferred option. The PSR (LANSCE) approach is to run the ring rf at an exact integer subharmonic (72) of the 201.25 MHz beam-bunching frequency, which then mandates that the beam chopper is always synchronized with the beam microbunch structure in the linac. This simplifies the beam chopper trigger circuit. It also requires that the beam revolution period in the ring be an exact integer subharmonic of the linac beam bunching frequency, so that microbunches are stacked on top of one another, rather than interleaved, during accumulation in the ring. This stacking is required by the PSR closed-orbit beam position monitor system, which operates on the 201 MHz rf structure. This microstructure would disappear very quickly if the beam bunches were interleaved. Even with stacking, the microstructure in the PSR persists for only about 10 μs, due to the beam momentum spread.

The other school (BNL) is concerned about space-charge issues in the ring if the microbunches are stacked rather than interleaved. Interleaving the microbunches requires that the ring revolution frequency and linac rf frequency are not harmonically related. The baseline SNS ring design (circumference = 220.67 meters) sets the ring period to about 841.2 ns (338.6 linac rf periods), for a 1-GeV proton beam on the central orbit. Any change in either the ring injection energy or the beam circumference in the ring (controlled by the B-field in the ring) will change the ring revolution period. Decoupling the ring rf frequency from the linac rf allows operation of the ring over a range of orbit radii (e.g., ± 2 cm) and injection energies (e.g., ± 10 MeV). However, interleaving will rapidly wipe out any vestiges of the 402.5 MHz rf microstructure, and therefore has an impact on the beam position monitoring circuit design, which must then rely on the beam gap signal or other persistent bunching structure.

The question of how then to set the ring frequency, if it is not harmonically locked to the linac rf, was discussed. One suggestion was to lock it to the beam gap frequency (which of course is locked to the beam chopper frequency during the early part of injection) which in turn is locked to the ring rf, but with chopper gate dithering to phase it to the linac microstructure. This seems to be a catch-22 situation.

The other suggestion was to make the ring rf frequency completely independent, and set it based on knowledge of the beam energy, and on the desired orbit radius in the ring. This latter method gives the most freedom in selecting the beam energy and the average orbit radius, but then makes the beam chopper in the linac injector, which is locked to the ring rf, asynchronous relative to the beam microstructure. (A possible approach to this issue is discussed in more detail in the section on the MEBT chopper, below).

Another suggestion, which at first seems to be different, but indeed may be the same, was to set the ring rf at a specific subharmonic of the linac rf frequency, say the 338th or 339th subharmonic, but to phase modulate both the ring rf and the beam chopper timing with an adjustable phase offset. This is in essence the same as operating the ring rf with a frequency offset from an exact subharmonic of the linac rf.

Once the ring frequency is set (assuming it is not an exact subharmonic of the linac rf), the other free parameter in the ring rf is the phase, which determines the angular position of the gap in the circulating beam when the extraction gate from the Fermi chopper enables the ring extraction trigger. The general consensus was that if the gate from the neutron chopper system was at least 1.2 μs, then ring extraction could occur at any time during the first full beam gap after the arrival of the neutron chopper gate. This means that the phase of the ring rf does not need to be synchronized to the neutron chopper. It was noted that at SSC, a system was devised by L.K. Mestha to synchronize and phase lock the low energy booster rf (a rapid-cycling synchrotron) to the medium energy booster rf (a ramped synchrotron) at the time of beam transfer. Such a scheme could possibly be used to synchronize the beam gap in the ring with the neutron chopper, if needed. This may be difficult however, because the beam is in the ring for a very small number of synchrotron oscillation periods.

MEBT Beam Chopper Synchronization

If the 1.19 MHz rf system determines both the ring rf and the MEBT beam chopper gate signal, the chopper gate signal is not synchronized to the 402.5 MHz microstructure, leading to the possibility of partially chopped bunches being accelerated in the linac. To synchronize these MEBT chopper beam gates with the 402.5 MHz rf, a synchronizer circuit is required. Its function is shown in Fig. 2.

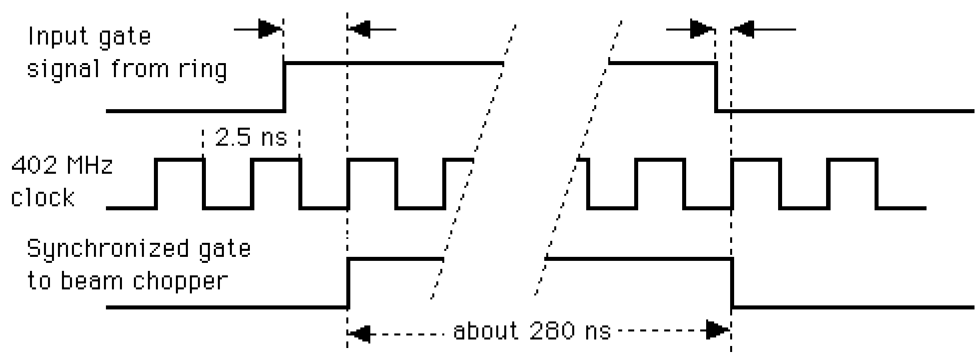

Fig. 2. Beam chopper gate synchronizer waveforms. The input gate signal is synchronized to the ring rf. The deskewed output gate signal is synchronized to the 402 MHz clock.

This synchronization could be accomplished using a high speed D-type flip flop. The maximum delay would be one period of the 402.5 MHz rf, or about 2.5 ns, as shown in the Figure.

Because of chopper beam stop power limits in the MEBT, much of the beam chopping must be done either in the ion source itself, or in the LEBT. Because the present plan is to ramp on the beam current at the beginning of every macropulse by the beam chopping system, all three choppers must be ramped from about 5% (beam-on) duty cycle up to about 67% (beam on) in 20 to 50 μs, as shown in Fig. 3, in a manner that does not lead to excessive beam power loss on any beam stop. This beam current ramp-up circuit has not yet been designed.

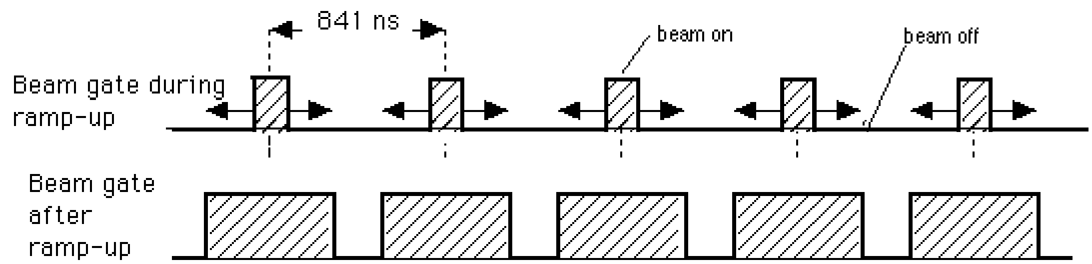

Fig 3. Beam current ramp-up, using the ion source, LEBT, and MEBT beam chopper systems. Arrows indicate the widening of the beam chopper gate during ramp-up.

Linac RF

The linac rf (including both the 402.5 and 805 MHz signals) will be supplied by a completely independent crystal oscillator circuit, and distributed by a phase-stable reference system. This signal is also supplied to the bunch-rotator cavity in the linac-to-ring beam transfer line. This very stable frequency reference is not locked to any other clock, or to the ac line.

Macropulse sequencing.

A sequencer will be required to trigger each individual linac pulse, and to determine what the sequence pattern will be for a series of linac macropulses. The present thought is that the sequencer would fully program one second (60 linac pulses).

For each individual linac macropulse, beam pulse permit signals will be required from every segment of the facility (Injector, Linac, Ring, and Spallation Target) before the linac rf modulators are pulsed. The only beam dump for the ring is the spallation target itself, so beam cannot be accelerated unless the spallation target is ready. A beam pulse permit signal from the ring, for example, will require that the pulse-forming networks (PFNs) for the extraction kicker are fully charged. This charging takes place in the 15 ms between linac pulses. A beam pulse precursor signal will trigger the linac modulator systems (defined to be T_0 time, no relation to the T_0 neutron chopper), which will then fill the linac rf cavities for about 50 to 100 μs before beam is injected. This timing sequence is outlined in Fig. 4. The beam chopping in the injector (Fig. 3) will inhibit any beam until permitted by the sequencer. This permit signal differs from Run Permit, which will (probably) remain enabled from macropulse to macropulse unless tripped. At the end of a predetermined number of microseconds (or beam chopper cycles), the injector choppers will inhibit further beam injection, and the accumulated beam in the ring will be extracted. Extraction from the ring must occur within a few microseconds after the end of injection because beam losses in the ring and the likelihood of beam instabilities and growth rates are highest at the high circulating currents at the end of accumulation.

If the neutron choppers are phase locked to the line frequency, and the line frequency can vary by say ± 200 ppm (± 0.01 Hz), the interval between successive neutron chopper gates can vary by as much as ±4 μs over periods of a few minutes. This slow variation in the neutron chopper frequency can probably be accommodated by allowing the time delay between the end of beam accumulation in the ring and ring extraction to vary accordingly. It is also possible to set T_0 to be a preset time before the next neutron chopper gate pulse, dependent on the exact chopper (and line) frequency.

Once the beam pulse is extracted from the ring, the beam-pulse permit signal is disabled until all PFNs etc. are recharged for the next macropulse. Excessive beam losses, or other events requiring a Fast Protect, can inhibit beam acceleration within about 20 μs at any time during accumulation. In this case the beam may be extracted early, but in every case to the spallation neutron target. In addition, follow-on macropulses could be inhibited by the Fast Protect system. Much can be learned from the present LAMPF operation in this area.

Because the SNS facility will eventually support at least two spallation targets with variable pulse sharing (e.g., 50/10, 30/30, etc.), and maybe even have a long pulse capability, one must allow for the eventual possibility of a linac macropulse pattern generator. For LAMPF, which can operate at 120 Hz, this pattern is 120 macropulse cycles long, and can generate any macropulse sequence that is consistent with the operating restrictions of various end stations (including beam current, macropulse length, macropulse spacing, repetition rates, etc.) .

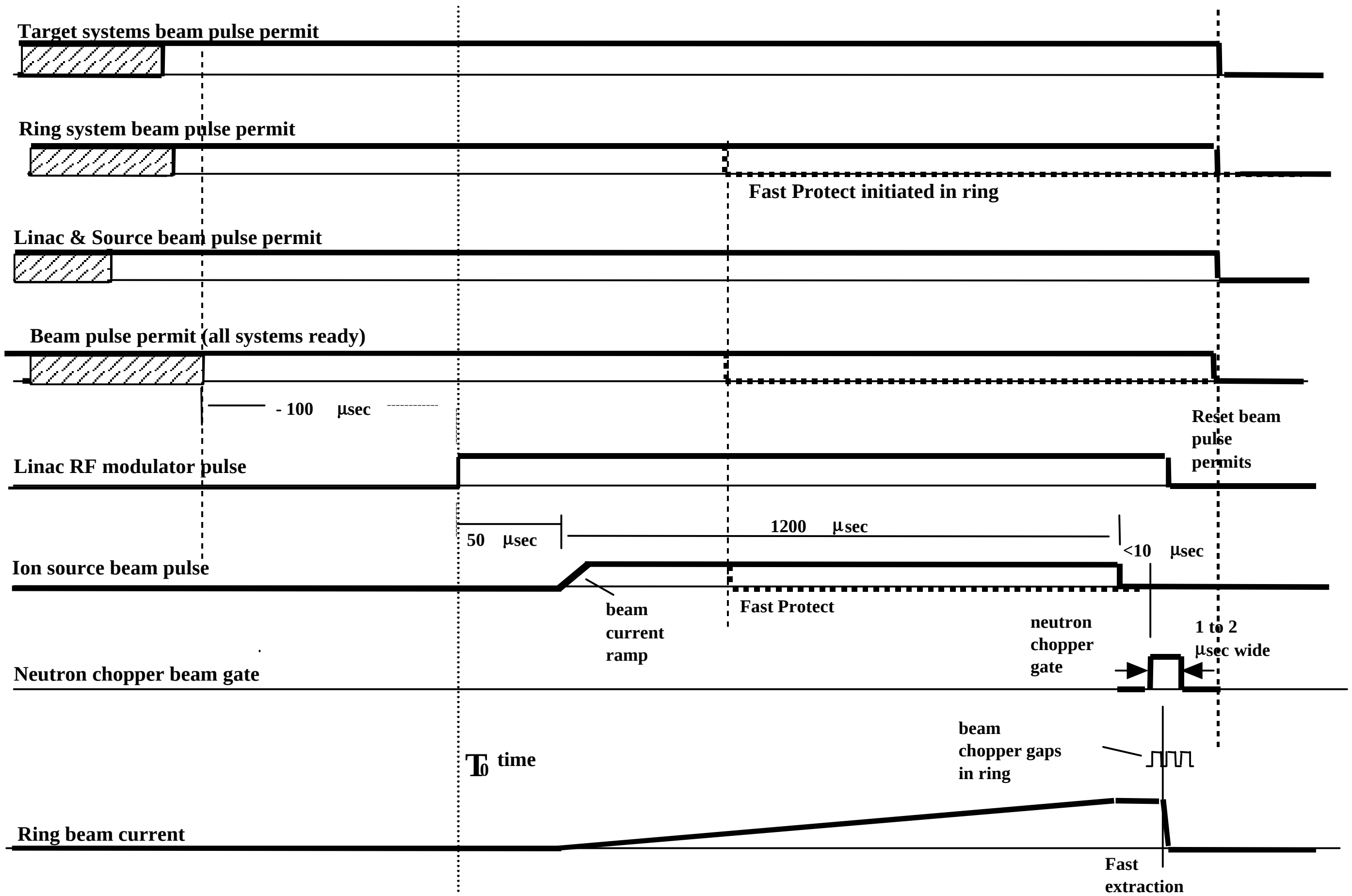

Figure 4. Approximate timing sequence for beam pulse

Conclusions

There was general agreement that the linac can run synchronized to the ac line. The experimenters believe that unequal pulse separation during two-target operation is not a concern. Line synchronization simplifies the linac modulator design and the issues related to beam optics in the klystron gun. The 60-Hz line signal will require extensive processing, both analog and digital, to produce a line-sync signal that is noise free and tracks the line frequency at a modest slew rate, compatible with the neutron choppers.

Development work is also required in the phaselock circuits for the neutron choppers to ensure that their frequency and phase tracks the line sync signal with minimum phase error, as long as the slewing rate is not excessive.

The ring rf frequency could be either slaved to the linac rf (i.e., a subharmonic), or be completely independent of the linac frequency. The latter provides more flexibility in operating the ring, but requires that the MEBT beam chopper be synchronized to the 402 MHz rf beam structure. This appears to be feasible using available ICs.

The beam ramp-up at the beginning of every macropulse is controlled by a combination of beam chopping in the ion source, LEBT and MEBT, in order to control the power of the chopped beam on every beam stop. No development work has been done in this area.

The timing sequencer for each beam pulse is similar to what now exists at LANSCE and IPNS, and there are no identifiable difficulties in building such a system for SNS. It was pointed out that it is easier to build an adequate system for timing and sequencing from the start, than to modify an old one that was not originally designed with the timing tolerances required for SNS.

Figure 4 shows a possible timing sequence for a single beam macropulse. A beam pulse permit is required from every system, injector, linac, ring, and neutron target, prior to every macropulse. This permits the linac rf modulator to pulse the klystrons at time T_0, to inject beam into the accelerator, and to accumulate it in the ring. At extraction time, the beam is extracted from the ring during a gate based on the phase of the master neutron chopper rotor.

Appendix 1 - Agenda

8:00	Coffee and Danish		
8:30	Introductions	Dave Gurd	
8:45	Introduction to the Issues	Jose Alonso	(ORNL)
9:15	User Requirements	Rob Robinson	(LANL/MLC)
9:45	Ring Timing Requirements	~~Y. Y. Lee~~ (Dave Olsen)	(BNL)
10:15	Coffee		
10:30	LANSCE Timing System	Larry Rybarcyk	(LANL/LANSCE)
11:00	The System at MLC	John Sandoval	(LANL/MLC)
11:30	Implications on RF Systems	Mike Lynch	(LANL/RF)
11:45	Line Measurements at ORNL	Jose March Leuba	(ORNL)
12:00	Lunch		
12:30	The approach at IPNS	Lawrence Donley	(ANL)
1:00	Discussion begins	Moderated by Gurd	

- Reminder of the Goals
- Summary of Requirements
- Alternative Approaches
    - synchronize with the line zero crossing
        - implications??
    - synchronize with a crystal
        - implications
    - intermediate solution
        - implications
- Recommendations

Appendix 2 - Speakers and Invitees

Los Alamos

Dave Gurd	(Chair)
John Sandoval	(Speaker)
Chris Rose	
Bob Hardekopf	
Mike Thuot	
Larry Rybarcyk	(Speaker)
Mike Lynch	(Speaker)
Rob Robinson	(Speaker)
Andy Jason	
Floyd Gallegos	
Matt Stettler	
Paul Tellerico	
Bob Shafer	

ANL

John Hammonds	
Kent Crawford	
Lawrence Donley	(Speaker)

BNL

John Smith	
~~Y.Y. Lee~~	(Speaker)
B. Oerter	

LBNL

Jim Greer	
Rod Keller	

ORNL

Jose Alonso	(Speaker)
Jose March-Leuba	(Speaker)
Dave Olsen	