Proceedings of International Collaboration on Advanced Neutron Sources (ICANS-VII), 1983 September 13-16
Atomic Energy of Canada Limited, Report AECL-8488

IPNS ACCELERATOR SYSTEM AND NEUTRON CHOPPER SYNCHRONIZATION*

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Introduction

Several of the neutron scattering instruments at the Intense Pulsed Neutron Source (IPNS) at Argonne use neutron choppers for monochromatization of the neutron beam. Since the neutron burst is produced by a proton beam extracted from the Rapid Cycling Synchrotron (RCS), precise synchronization must be maintained between the RCS and the chopper aperture to minimize the degradation of energy resolution. The first attempts at synchronization were made in 1978 on the ZING-P' facility with a single chopper. Synchronization was further complicated after IPNS began operating in 1981 when a total of three chopper experiments came on-line. The system in use during that period of time was able to maintain synchronization with typical data collection efficiencies ranging from 20 to 70%. A synchronization system improvement, installed in late 1982, increased the data collection efficiencies of all the IPNS chopper systems to 99+%. The development of the RCS and neutron chopper synchronization system is described together with a detailed description of the present system.

RCS System Description

The RCS was originally designed to operate at 30 Hz synchronized to the 60 Hz power line. The synchrotron ring magnets are part of a biased 30 Hz resonant circuit which is driven by a 24 phase power source made up of two solid state power supplies.[1]

*Work supported by the U. S. Department of Energy.
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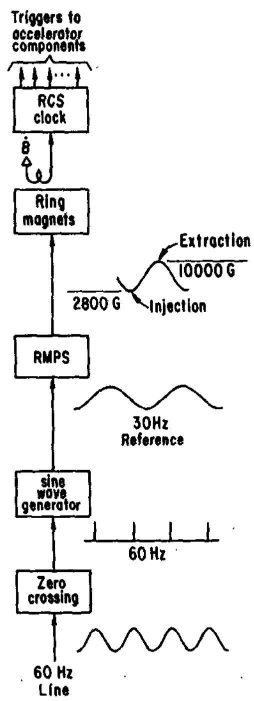


Fig. 1. Accelerator timing block diagram.

The reference 30 Hz sine wave for the ring magnet power supply (RMPS) is generated from the 60 Hz power line by an analog series approximation circuit.

The timing for the other accelerator components (H^- ion source, linac, injection and extraction magnets, etc.) is provided by the RCS clock which is synchronized to the magnetic field in the ring magnet by monitoring the zero crossings of the $\dot{B}$ signal from a pickup loop in one of the magnets. The clock has an uncertainty of ±0.5 μs and all timing adjustments have a resolution of 10 μs. A block diagram of the accelerator timing system is shown in Fig. 1.

The proton beam is extracted from the RCS in a single turn by a fast, 100 ns rise time, kicker magnet,[2] a pulsed transformer septum magnet[3] and a conventional dc septum magnet. The timing pulse from the RCS clock to the extraction kicker system arms the trigger circuitry. A signal derived from the circulating beam triggers the high current thyratron switches to charge the magnet after the tail of the circulating beam bunch has passed the kicker magnet creating an uncertainty of ±100 ns in the actual extraction time in respect to the timing pulse from the RCS clock.

Chopper System Description

The neutron beam chopper is a cylinder made of a neutron absorbing material with a curved slot containing a slit package which permits neutrons to pass through. The revolution frequency, and the width and curvature of the slits determine the range of energies that are transmitted to the experimental sample. The chopper is rotated at a frequency multiple of 30 Hz (typically 270 Hz) by a fractional horsepower synchronous motor. The motor-chopper assembly is enclosed within a vacuum tight housing which contains windows for neutron beam entry and exit. Cooling for the motor and bearings is provided by water cooling loops on the outside of the vacuum enclosure at the armature end and by a 0.5 torr helium exchange gas within the enclosure which provides cooling by convection but does not create significant aerodynamic drag on the chopper rotor. The total amount of cooling provided established the practical limit on motor size. The chopper rotor and vacuum enclosure are shown in Fig. 2.

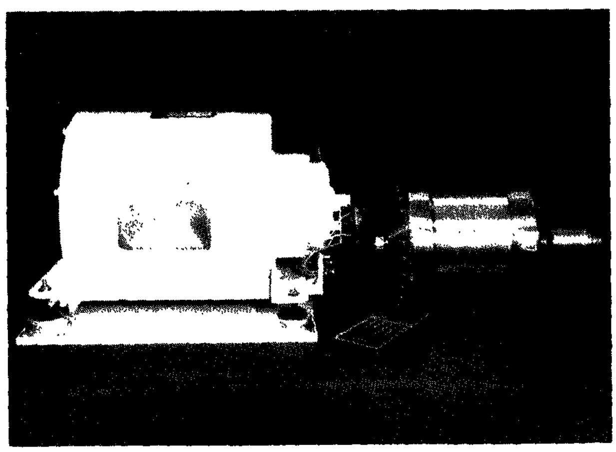
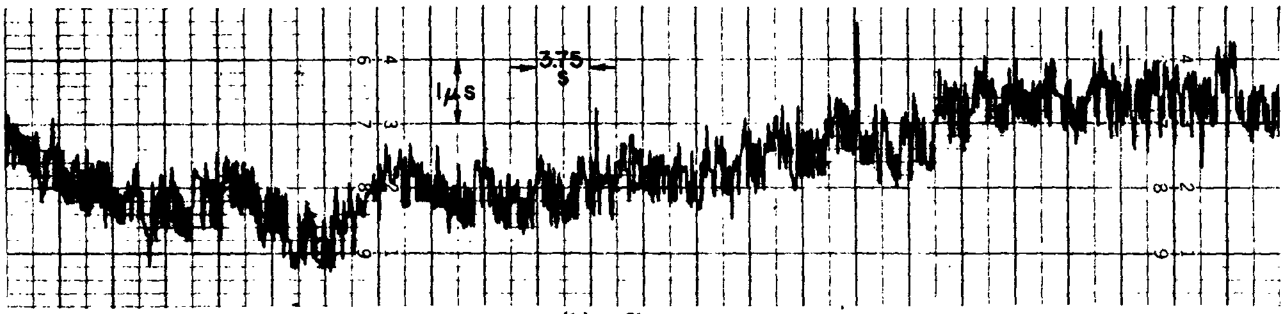


Fig. 2. Chopper rotor and vacuum enclosure.

(a). Long-term.



(b). Short-term.

Fig. 3. Variation of the period of the 60 Hz line.

The chopper drive system provides the power required to operate the chopper at a chosen speed, monitors the chopper operating parameters and shuts down the chopper power if a potentially damaging condition exists. A frequency synthesizer produces two phase sine waves in the frequency range of 1 Hz to 960 Hz to drive the chopper motor power amplifiers. The synthesizer also has provisions to be phase locked to an external 30 Hz reference and provide an output at any harmonic of 30 Hz. A magnetic pickup, located on the chopper housing, provides a signal indicating the position of the chopper opening. A separate accelerometer is mounted on the armature bearing end plate and acts as a monitor for chopper vibration.

Initial Synchronization Attempts

The first logical step for synchronization, at least from the accelerator standpoint, was to operate the chopper system synchronized to the 60 Hz power line. Investigation of the power line stability was begun and the "stable" line frequency was found to be unacceptable. A typical plot of long-term 60 Hz line period is shown in Fig. 3(a). Short-term variations are shown in Fig. 3(b). With the chopper's high moment of inertia, the low torque motor had no possibility of tracking the short-term variations of the power line. The phase change response of the chopper magnetic pickup signal to the reference drive signal is shown in Fig. 4 for a 0.001% change in the frequency of the drive signal. As a point of comparison, a 1 μs change in the 60 Hz period is equivalent to a 0.006% change. The difference in the large inertias and time constants of the chopper system and the RCS ring magnet system made synchronization to the line impossible.

The next synchronization attempt was to operate both systems locked to a common crystal oscillator.[4] This was a familiar mode of operation for the chopper system since it is used at reactor facilities, however, it was a totally new approach for the accelerator. The output of a 3.932 MHz oscillator, stable to ±1 part/million (ppm), was divided down to generate the required 60 Hz pulses for the RMPS, as well as the drive frequencies for the chopper. Studies of extraction from the RCS were conducted and the timing limits for efficient extraction and transport were established. Efficient extraction was possible within ±250 μs of the peak of the ring magnet field and within ±120 μs of the peak of the extraction septum pulse. Thus, it was possible to allow the chopper to initiate the extraction from the RCS within the efficient extraction time, the extraction window (EW). Two different means of controlling extraction were attempted. The first allowed the chopper system to control the triggering time of the extraction septum, with the kicker trigger occurring a fixed time after the septum. The second method fixed the septum time to the ring magnet field and allowed the chopper to control the arming time of the kicker system. Although the former allowed the use of a large EW

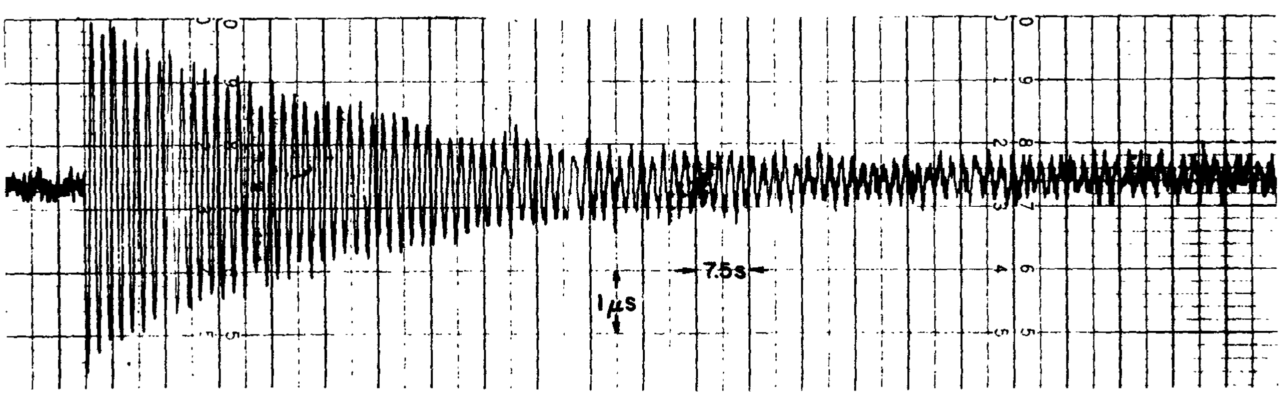


Fig. 4. Chopper phase oscillation caused by a 0.001% change in driving frequency.

(±250 µs), some degradation in the neutron energy resolution was detected due to the additional timing uncertainties caused by the longer delay between the chopper extraction command and the neutron burst from the target. Therefore, the second method became the standard mode of extraction control.

Further problems were encountered due to phase shifts between the master clock, the RMPS voltage and the ring magnet magnetic field. The phase shifts between the RMPS voltage and magnetic field were primarily caused by temperature variations in the RMPS resonant circuit and the subsequent detuning. This effect was minimized by installing a circuit to vary the capacitance of the tuned circuit in small steps to maintain the system within ±150 µs of resonance. Due to its nature, this was a relatively long-term effect. Several other factors on phase shifts were short-term. The first was caused by "beam noise", the coupling of circulating beam into various control lines causing instabilities in RMPS control circuits such as the sine wave generator and RMPS regulator. The second was caused by power line related ripple in various RMPS control circuits causing variation in system operation, a problem which due to the asynchronous operation to the line became a factor in many RCS systems, and in beam acceleration efficiency. The effect of "rolling" in respect to the power line frequency resulted in a 10% lower average current delivered on target. In addition, since the rate of "rolling" varied as the line frequency varied, the tuning of the accelerator was difficult because of the constantly changing conditions. Attempts were made to pinpoint the various causes for the beam handling instabilities. The effect on the RMPS caused variations in the injection field creating changes in the beam noise pattern which in turn affected the RMPS causing a further change in the injection field, etc.; a servo loop with positive feedback. Some variation of the injected beam properties due to ripple on the 50 Mev transport line magnets were also noted, but the position and size variations were too small to account for the beam instabilities. Any variation in the energy distribution of the injected pulse due to power supply ripple in the linear accelerator could not be studied for lack of an injection energy spectrometer.

After careful study, the effects of the RMPS were minimized; however, the total phase shift between the master clock and the ring magnet field and subsequently the EW remained in the range of ±200 µs. The chopper control system was redesigned to enable the chopper to track the phase variations of the EW. However, due to the low torque of the chopper drive motor, the maximum correction rate was limited to 0.5 µs/s since a higher rate would cause demagnetization of the motor armature. Because of the low correction rate, the chopper was not able to maintain synchronization with the RCS for 100% of the time. In fact, with multiple chopper operation, since only the master chopper can control extraction and because of the unequal inertias and time constants of the choppers, the data collection efficiency of the slave choppers was as low as 20%.

Synchronization System Operation

The operation of the RCS on the master clock is straightforward and has already been described in the previous section. The interfacing of the RCS to the chopper electronics and chopper system operation will be described here. Figure 5 shows the block diagram of the system.

In order for the chopper to stay in phase with the RCS, the chopper frequency $1/\tau_c$ must be a multiple of the 30 Hz RCS frequency. The fundamental condition

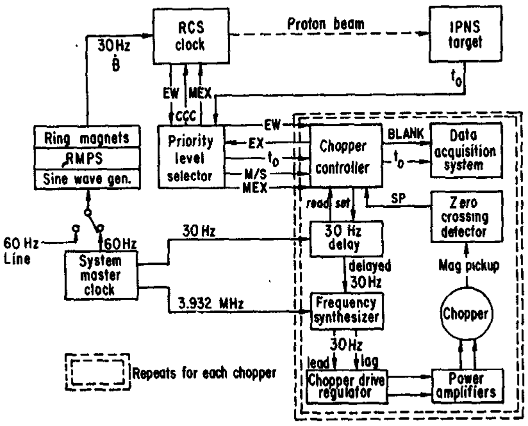


Fig. 5. RCS and neutron chopper synchronization system block diagram.

which must be met is that the chopper opening time follow the protons on target signal (t_o) by the required phase delay time T_c, within a tolerance of ΔT_c. The chopper phasing system controls proton beam extraction and, therefore, t_o, so all that is required to establish the desired phase is to send an extraction command (MEX) at a time such that

$$t_o + T_c = t_2 + \tau_c \quad ,$$

where t_2 is the chopper opening before t_o. The EW is provided by the RCS clock during which MEX is accepted; if an MEX arrives within this window then it will be used, but only if the chopper can control (CCC) level is true. The CCC is used to make it possible for the RCS to control extraction on those RCS cycles when a MEX cannot be issued within the EW; when the CCC is false, the RCS clock will generate its own extraction trigger at the midpoint of the EW, the optimum instant from the accelerator's point of view. As long as the CCC is true, the RCS clock will wait for a MEX until the last possible moment; if none arrives, the beam will be extracted at the trailing edge of the EW. In this case, the pulse will not be usable by the chopper experiment, but will be available to other experiments. The phasing system checks every t_o pulse to make sure that the phase condition is satisfied, i.e., that

$$t_o - t_2 = \tau_c - T_c \pm \Delta T_c/2 \quad .$$

If this condition is not satisfied, an inhibiting level is sent to the data acquisition system so data will be accumulated only for correctly phased pulses. The final function of the phasing system is to adjust the phase of the chopper with respect to the RCS when necessary in order that a legal MEX (i.e., in the EW) can be sent. This is accomplished by introducing a delay in the 30 Hz pulses to the frequency synthesizer from the master clock.

The priority level selector is the communications link to the RCS. It also communicates with up to six chopper controllers and prioritizes the information it receives from them. Each controller receives EW and t_o from the priority level selector and sends back its own extraction trigger, EX. The priority level selector sends to the RCS clock, as the MEX, the highest priority legal EX signal it receives for each RCS cycle. Thus, if the first priority EX signal is not within EW, the second priority EX will be used, etc. If there is no EX from any of the six inputs which is within EW, the priority level selector sets the CCC false until a legal EX pulse comes in again from one of the chopper controllers. At any instant, the highest priority chopper providing a legal EX is defined to be the master, all others are slaves. This status information is sent back to each chopper controller and is used during phase shifting. Only the master chopper tracks the EW, all the slaves track the MEX, the extraction command issued by the master chopper.

Although it is not shown on Fig. 5, the system also contains a 60 Hz backup clock. In the event of interruption of the master 60 Hz signal to the RMPS, the backup clock synchronously switches the RCS over to its own 60 Hz reference signal. This is done to protect the RMPS from possible damage due to sudden removal of the reference 30 Hz sine wave and to prevent the RCS from shutting down when something goes wrong with the master clock or associated cabling. The backup clock does not provide any signals to the chopper system, so the choppers do not synchronize to the RCS in this mode of operation.

Synchronization System Improvements

Although tolerable, the data collection efficiency of the chopper experiments was far from ideal and further methods were investigated to improve the efficiency. It did not take long to realize that the RMPS could be phase shifted much more rapidly in respect to the master clock than the 0.5 µs/s maximum chopper correction rate. A system was designed and built to phase shift the RMPS and to interface to the existing controls with the least amount of effort. The changes to the basic system of Fig. 5 are shown in bold on Fig. 6.

The basic concept of neutron chopper controlled extraction remained the same, however, the EW was replaced by two: 1) the RCS extraction window (REW) and 2) the chopper extraction window (CEW). The REW is generated the same way as the EW and occurs centered about the peak of the extraction septum field and denotes the maximum allowable time range for extraction. The CEW is identical in width to the REW, but starts on the positive transition of the 30 Hz square wave from the master clock. The chopper phasing circuits use the CEW as the reference to phase the choppers so that the EX occurs in the center of the CEW. Since the CEW is referenced directly to the same clock that provides the reference signal to all the choppers, the phase relationship between the clock and the CEW is fixed and, therefore, no phase corrections are required by the choppers except for any internal mechanical variations, such as, bearing

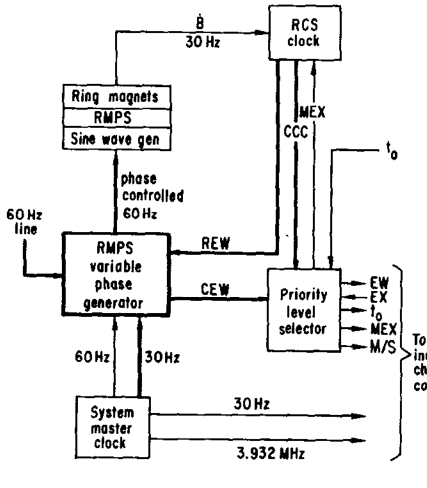


Fig. 6. Synchronization system improvements.

wear. In addition, the CEW provides a fixed synchronization reference point for choppers operating on various harmonics of 30 Hz.

The RMPS variable phase generator monitors the two windows, CEW and REW, and maintains synchronization between the two by phase shifting the RMPS and, therefore, the whole accelerator system. This is accomplished by varying the delay of the 60 Hz pulses between the master clock and the RMPS sine wave generator. No correction is made if the phase difference between the REW and CEW is less than 50 µs. If the phase difference exceeds the window width, corrections are made at a rate of 450 µs/s. When the phase difference is less than the window width, corrections are made at a rate of 30 µs/s. Once a correction is begun, it continues until the phase error is zero. Phase corrections are enabled only when the RMPS is operating synchronized to the master clock and the beam is on. The RMPS variable phase generator has a control range of ±5 ms. If the control range is exceeded during a correction, the electronics switches the RMPS to the backup clock, resets the delay to midrange, switches the RMPS back to chopper clock and resumes correction. A manual delay is included to allow the RCS operator to set the variable delay to the center of the control range.

As part of this improvement, the direction of the CCC signal was reversed. It now provides a status indication to the chopper priority level selector that, when true, the RCS clock is accepting the MEX command. It is true only when the phase error between CEW and REW is less than the window width. When the phase error is greater than the window width, CCC is false and extraction occurs at the midpoint of REW.

An additional feature of the RMPS variable phase generator is the synchronization of the transfer from master clock to 60 Hz line operation. Since the accelerator operation is more stable when the RMPS is operating synchronized to the 60 Hz line, whenever the chopper experiments are not operating even for short periods of time, the accelerator is operated synchronized to the line. The synchronized transfer feature allows the transfer to be made in both directions without shutting down the beam; and for a fast cycling accelerator, the previously required 5 minute switchover time resulted in quite a few missed pulses on target.

Conclusion and Future Plans

The final evolution of the RCS and neutron chopper synchronization system has brought about data collection efficiencies of 99+% to all the neutron scattering experiments using choppers. However, it has not eliminated the accelerator instabilities related to the beat frequency of the master clock to the 60 Hz line. This manifests in a 10% lower average current delivered on target with master clock operation compared with 60 Hz line operation.

Work is presently underway on a compromise solution, a master clock which tracks the variations of the 60 Hz line within the tracking capabilities of the chopper system. Additional circuitry would improve the tracking capability of the chopper by damping any oscillation induced by the phase shifting required by the new clock. Initial tests of a prototype system look promising but an operational system is still in the future.

Finally, the ideal system, from the accelerator's point of view, is under consideration; a redesign of the total chopper system to allow the chopper to track the 60 Hz line.

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