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INTENSITY STABILITY IMPROVEMENTS FOR THE INTENSE PULSED NEUTRON SOURCE ACCELERATOR SYSTEM*

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Introduction

The Intense Pulsed Neutron Source (IPNS) accelerator system consists of a 750 keV Cockcroft-Walton preaccelerator, 50 MeV linear accelerator and a 500 MeV Rapid Cycling Synchrotron (RCS).[1] The accelerator system accelerates over 2.5×10^{12} protons per pulse at a 30 Hz rate to strike a depleted uranium target for producing neutrons, which are used for neutron scattering research. Since beginning operation in 1977, the beam intensity has been steadily increasing with improvements in various systems, such as a new H^- source,[2] improved correction magnet systems,[3] etc. Instabilities created by the higher intensities have also been brought under control.[4]

The accelerator system was designed to operate synchronized to the 60 Hz power main. This meant that any power supply ripple was also synchronized to the accelerator and would not create a significant problem. Therefore, only minimal filtering was provided in many of the accelerator components, but this did not affect accelerator performance during power main synchronized operation. However, rotating neutron choppers, experimental apparatus used to select a particular energy from the total neutron spectrum, were installed and from the accelerator standpoint upset the delicate balance. The desired energy resolution on the neutron chopper instruments required them to be synchronized to the acceleration cycle and specifically to extraction from the RCS to within 1 μs. Because of relatively high inertia and low torque of the chopper driving motors, the neutron choppers were not able to track the variation of the power main frequency and therefore the acceleration cycle. As a result, both the accelerator and the neutron choppers were synchronized to a common stable clock,[5] causing the accelerator to slip in phase with the power main. This slippage accentuated the effect of the power main related ripple in various accelerator components with a subsequent reduction of beam intensity stability. Numerous studies were made to determine what systems were the major contributors to the instability. The results were as follows: preaccelerator -- variation in beam intensity from the preaccelerator; linear accelerator -- variation in the rf gradient level; 50 MeV transport line -- variation in numerous power supply currents (primarily bending magnets); and RCS -- variation in the ring magnet power supply causing changes of the injection field.

The variation of the beam intensity was in itself not very disturbing, however, since the RCS was operated near the beam instability limit, the average injected intensity had to be reduced by 10% to allow for the variation. The variation of the rf gradient affected the injected beam energy spread and consequently the particle distribution in the RCS rf bucket. This increased the probability of high energy instabilities. The variation of the transport line magnets affected the injection position and angle and together with the variation of the injection field, reduced the effective aperture. Individually, each of these variations were subtle, but occurring together, they created a serious problem. What made matters worse, they were continuously changing as the power main frequency varied in respect to the stable clock, making it difficult for the accelerator operators to tune and minimize the adverse effects. Adding additional filtering or replacing power supplies with better regulation was considered but the large effort and cost requirements precluded this idea. A decision was made to design feedback systems for each of the four major causes of the instability: the rf gradient level of the linear accelerator, the intensity and position of the injected beam and the level of the injection field. Both the linac rf gradient and the ring magnet power supply (RMPS) already had low gain, high frequency feedback loops, but it was clearly evident that high gain, low frequency loops were also required.

Feedback Description

RF Gradient Level

Long-term regulation of the linear accelerator tank rf gradient is achieved utilizing a CAMAC based data acquisition and control system consisting of an analog to digital converter, a power supply controller, an output register module, and a control panel.

The control panel consists of a four digit digital readout (DRO), a readout selector switch, a gradient adjustment knob, setpoint select/deselect pushbuttons, an inhibit switch and associated light emitting diode (LED) indicator lights. The rf gradient level from one of the tank pickup loops is sampled by a 12 bit sample and hold converter. A Kinetic Systems model 3162 power supply controller provides two independent analog voltages via 12 bit digital to analog converters, five digital output control signals and nine status input signals. The latter are used to sense any input commands originating from the control panel. One of the analog outputs provides the correction voltage to the input amplifier of the rf transmitter plate modulator. The 48 bit output register is used to output DRO and LED information to the control panel.

During normal accelerator operation, the tank rf gradient level is sampled once each acceleration cycle and read by the control computer. The computer maintains an average of the last "N" cycles ("N" being determined by the accelerator repetition rate) updating the selected display approximately twice a second. The regulation process is started by the accelerator operator adjusting the "gradient" knob until a desired gradient level in the range of 1.150 V to 1.300 V is reached. The operator then pushes the "select" button to inform the computer, which then

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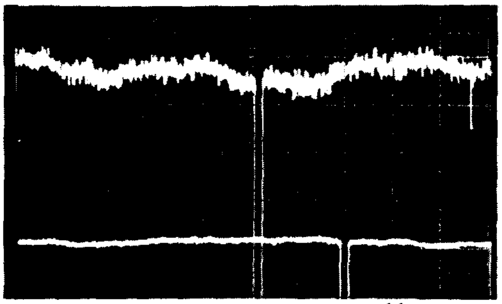

Fig. 1. Injected beam intensity ($2x10^{11}$/division)
Top: without feedback; Bottom: with feedback.

compares "N" cycle averages to the selected set point. Any deviation greater than ±1.5 mV from the setpoint generates a correction voltage which is sent to the power supply controller. Control may be terminated in several ways: the operator could turn it off by pressing the "deselect" button or throwing the inhibit control switch. The computer will also inhibit control if any of the limits are exceeded. Since precise regulation is only required during beam on time, the control system is externally inhibited at all times when beam is not being accelerated in the linear accelerator.

Injected Beam Intensity

This feedback loop was the easiest to implement and was the first to go into operation. Since the magnetron H^- source required operation at a constant temperature,[2] a 750 keV beam chopper[6] was installed to shape the beam pulse before injection into the linear accelerator. The control system for the beam chopper was designed to allow the operator to easily control (open-loop) the pulse width and thereby intensity. Thus, it was relatively simple to effect closed-loop control. Since the intensity variation from the H^- source had minimal loading effects on the linear accelerator, it was decided that the sensing of the intensity should be done in the 50 MeV transport line to the RCS. Two beam current transformers (toroids) located at the input and output of the transport line already existed. The two signals from the toroids are integrated by two integrators with different gains. The outputs of the integrators are compared to an operator controlled common reference level. When the reference level is reached, a signal is sent to the 750 keV beam chopper to terminate injection. When injection is terminated by the output toroid, all is considered normal. However, if injection is terminated by the input toroid (the integrator with the lower gain) a warning is flashed to the operator that the transport efficiency has dropped. This detection threshold is easily adjustable by varying the ratio of the gains. Typical variation of the injected beam intensity with and without the feedback loop is shown in Fig. 1.

Injected Beam Position

Injection into the RCS utilizes a set of three bumper magnets to deform the orbit and a stripping foil to strip H^- to H^+. This is shown in Fig. 2. What is not shown on the figure is a segmented Faraday cup (SFC) located downstream of the second bumper magnet (B2) on the inside radius. It is well out of the way of the circulating beam and intercepts only

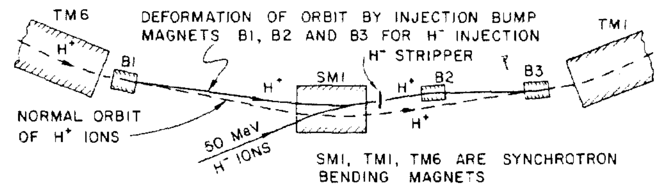

Fig. 2. Injection into the RCS.

partially stripped H^0 and the H^- beam that does not go through the foil. The analog signals from each of the segments are multiplexed to the control room. The operators use this signal to monitor the position of the beam on the stripping foil by purposely allowing <1% of the injected beam to miss the foil. The variation of the bending magnets in the transport line does not affect the transport line efficiency, however, the variation in injection position does affect the RCS operation. The operators were able to compensate the effect by continuously varying one of the last two bending magnets in the transfer line.

The injected beam position feedback circuit replaces the operator in that manual feedback loop. The signals from the segments of the SFC where the H^- beam normally exists are integrated every acceleration cycle. The operator adjusts the amount of H^- on the SFC and takes a reference. The value of the integrator is digitized by a 12 bit analog to digital converter and is stored in a memory. The subsequent integrator signals are compared to the reference and if an operator controlled limit is exceeded for a predetermined number of cycles, a correction signal is sent to the next to the last bending magnet power supply to change the current and reduce the error to zero. The correction rate is also operator adjustable. Limits are provided to prevent a large change in case of a loop malfunction and the loop is disabled when the injected beam intensity drops below 5×10^{11} protons per pulse to prevent correction with inadequate information. The effectiveness of the feedback loop is shown in Fig. 3 which plots the output of the SFC integrator for over 2000 consecutive acceleration cycles.

Injection Field Level

The accelerator magnetic guide field, generated by the RMPS, is a 30 Hz sine wave offset with a dc bias.[7] The overall effects of synchronizing the RMPS to a stable 60 Hz reference resulted in a maximum ±8 G deviation of the 2800 G injection field. This is

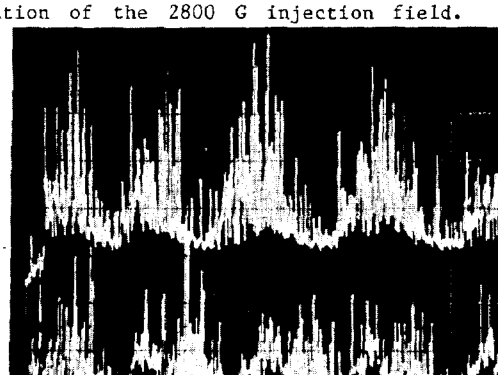

Fig. 3. Injected beam position (20 mV/division)
Top: without feedback; Bottom: with feedback.

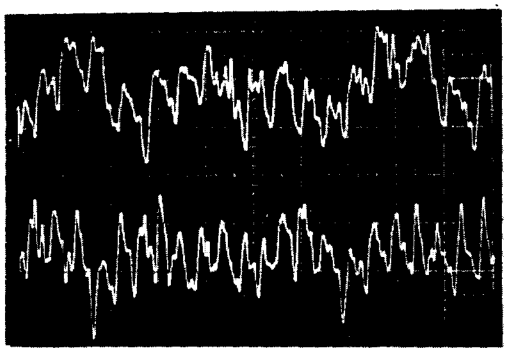

Fig. 4. Injection field (4G/division)
Top: without feedback; Bottom: with feedback.

about 40% of the available horizontal aperture. Control of the injection field is provided by adjustment of the RMPS dc offset through a digital to analog converter which varies a stable dc reference signal to the RMPS regulator circuitry.

The RMPS minimum field trim regulator provides additional control of the injection field by manipulation of the RMPS dc offset bias. Sampling and holding the RMPS shunt current signal at the appropriate time provides a measurement of the injection field. Filtering and comparing this signal to a stable reference voltage provides a difference error signal of ±63 mV/G. When the error signal exceeds a preset level, the appropriate high/low comparator will gate correction strobe pulses to the RMPS dc digital to analog circuitry. Once started, correction pulses continue until the error signal becomes zero.

Referenced to a stable 60 Hz source, the ±8 G deviation of the injection field is modulated at a rate proportional to the beat frequency with the power main. Due to the large inertia of the RMPS system and variable beat frequency, operator adjustment of the rate of correction and error limit (WB) have been provided. Fine control of the nominal field setting (B_{adj}) is also available. The control range for WB is from ±0.5 G to ±6.2 G and the "rate" of correction is variable from 0.4 G/s to 2.5 G/s while the B_{adj} range is from 2788 G to 2812 G. The level of the minimum field with and without the feedback for >2000 pulses is shown in Fig. 4.

Conclusions

The four feedback systems described above have made a significant improvement in the operation and intensity stability of the IPNS accelerator system. As stated before, each of the effects were subtle, but required the operator to continuously tune each of these systems to maintain stability. And four-handed operators are hard to come by. Since the installation of these feedback systems, the operator has been able to optimize other machine parameters with significant improvements. This is shown in Fig. 5 which is a plot of weekly averages of time averaged current on targets per time averaged current of beam loss in the RCS. The weekly averages begin in November 1983, and cover the weeks of chopper synchronized operation until May 1985. It is clearly evident that the efficiency improved significantly shortly after the feedback loops were installed prior to week number 17. The drop shown for week number 23 was caused by an aperture restriction in the RCS which has since been repaired. The last data point is a partial weekly average at the time of writing.

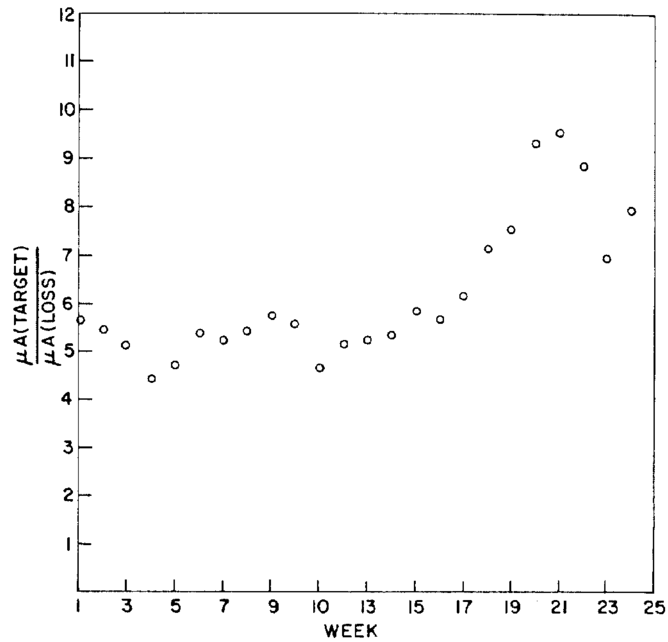

Fig. 5. Efficiency improvement.

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