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Status of the Intense Pulsed Neutron Source Accelerator System*

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Introduction

The Intense Pulsed Neutron Source (IPNS) Accelerator System has been operating since 1977. The first two years were as part of the innovative ZING-P′ program. Since that time the performance of the accelerator system has constantly improved and present currents exceed those of ZING-P′ days by 250%. The accelerator availability, long the pride of the accelerator operations group, has remained excellent, averaging over 90%. Problems with equipment and beam handling have been encountered and have been surmounted. The remainder of the text covers the high points as well as the low of the last two years of the IPNS Accelerator System operation.

Operating Summary

The performance of the IPNS Accelerator System continues to set milestones for proton synchrotrons. At 8:24 a.m. on Sunday, June 10, 1984, the accelerator delivered the billionth pulse of protons to the neutron generating target. At the present time, over 1.3 billion pulses have been delivered. A new record monthly average of 12.5 μA time averaged beam current on target was achieved during February of 1985. That same month, peak currents of 15.6 μA were reached. The following month, March, 1985, accelerator availability hit a peak of 97.3%. During the week of June 20-26, 1985, a new high weekly average of 13.6 μA was achieved. These are not isolated records! Since the last status report at the International Cooperation on Advanced Neutron Sources (ICANS-VII) at Chalk River[1] held in September of 1983, the time averaged beam current on target has increased by almost 40%. Figure 1 shows a more detailed record of target current for that period of time. Figure 2 shows accelerator availability during the same period. An operating summary from the start of IPNS operation in November 1981, until the time of writing is shown in Table I.

With the higher intensity operation, even more emphasis has been placed on keeping the beam losses in the accelerator as low as possible. The reason for this is clearly evident in Fig. 3, which shows that the largest amount of downtime during the past year is due to cooldown - the time required for residual radioactivity to decrease to a low enough level so that a fault in the accelerator tunnel can be repaired. The accelerator current we achieve is limited by the losses we allow. We do not strive for higher currents until the losses are under control. The average beam losses in the accelerator are held

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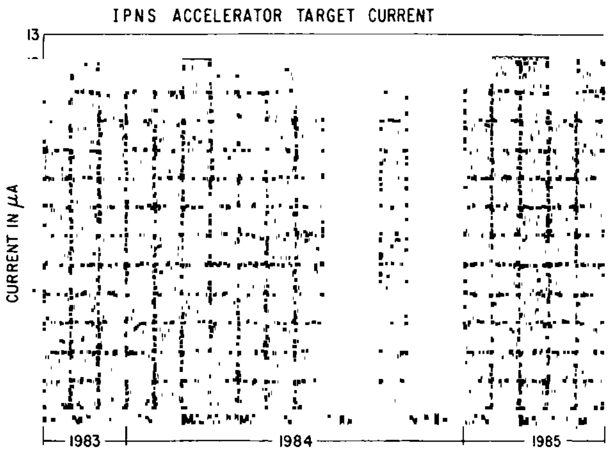

Fig. 1.

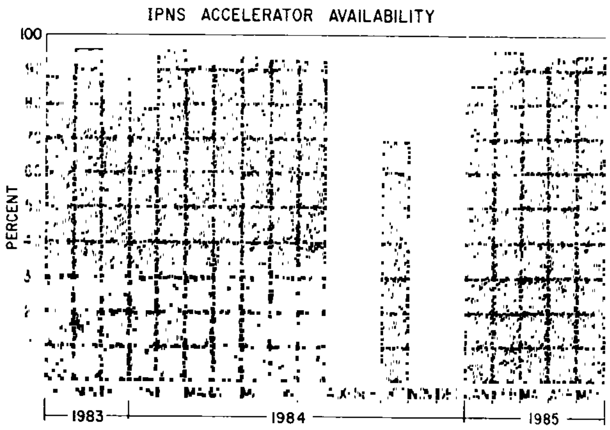

Fig. 2.

below 3.5 x 10^{11} protons per pulse (1.7 μA time averaged current). The majority of the beam losses (approximately 80%) occur below 60 MeV. Automatic protective interlocks will inhibit the beam if 2 x 10^{13} protons are lost in a second. Twenty new scintillation beam loss monitors provide detailed loss information to the operators from various parts of the accelerator. These loss monitors provide much more sensitivity than any of the other diagnostics. Losses of <<1% can be easily observed. The accelerator lattice lacks trim dipole magnets which are required for good loss control. Manipulation of the beam injection quality with 50 MeV transport magnets is a complex and inexact method of loss control, but it is the one we use most.

The quest for both higher intensity as well as high availability is not an easy one and always requires control of the impulse to try for record beams. Maintainability is uppermost on our priority list. In a facility of this type, some experiments last only a few hours and lost experimental time is not easily rescheduled. But even the best laid plans sometimes fail. In November 1984, the pulsed extraction septum magnet failed when a water leak developed in one of the cooling loops. This magnet had pulsed for over 1.5 billion pulses. In fact from a mechanical stress aspect, one can consider 3 billion pulses, since

Table I.

Accelerator Operating Summary

	Nov. 1981- July 1982	Oct. 1982- July 1983	Oct. 1983- July 1984	Oct. 1984- June 1985
Proton beam energy (MeV)	400	450	450-500	450
Average beam current (μA)	8.02	9.21	11.46	11.93
Operating efficiency (%)	88.9	90.2	90.4	91.1
Scheduled operating time (hrs)	3358	3833	4750	2797
Available operating time (hrs)	2985	3458	4294	2547
Total pulses on target	2.94×10^{8}	3.33×10^{8}	4.23×10^{8}	2.66×10^{8}
Total protons on target	4.44×10^{20}	6.39×10^{20}	1.01×10^{21}	6.61×10^{20}

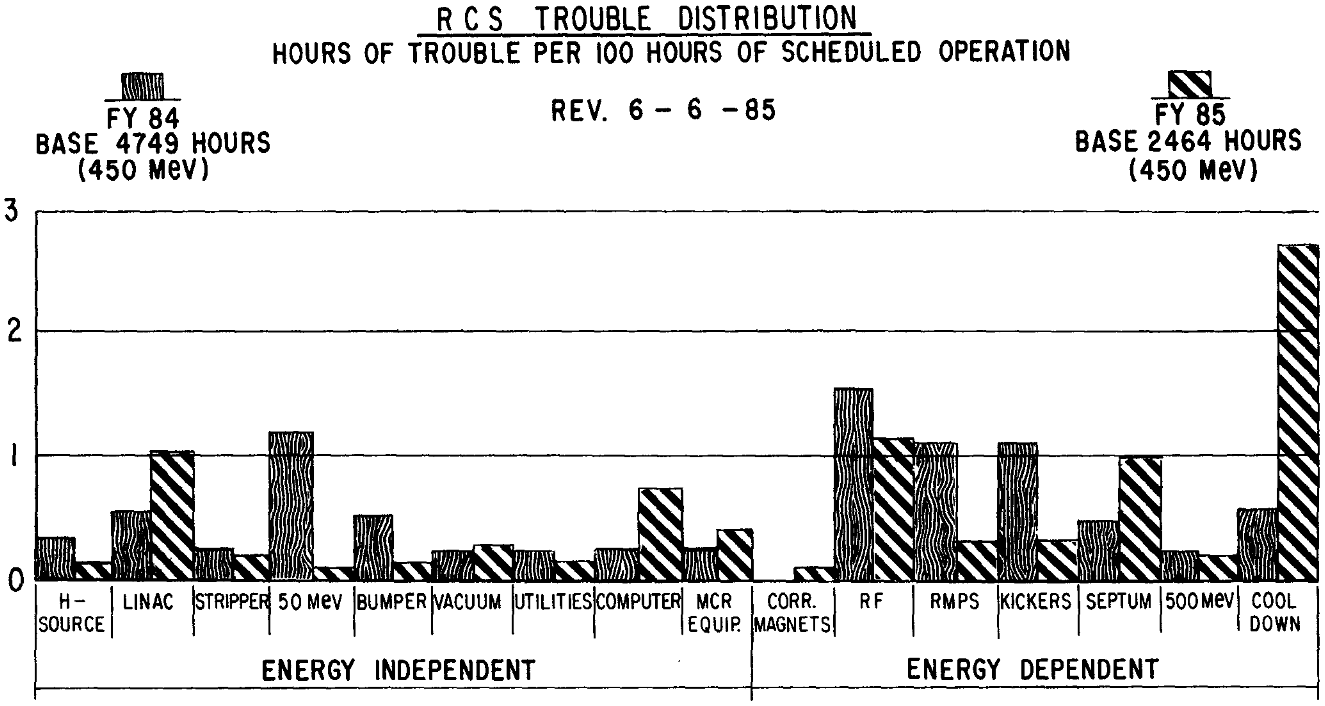

Fig. 3.

after each pulse, the magnet is pulsed with a reverse current pulse at approximately 80% of peak current to reset the core of the transformer type magnet[2]. Although the magnet was designed for relatively easy removal from the vacuum box (fast disconnect power and water feeds), the small size of the synchrotron tunnel did not allow for the installation of the required additional rigging equipment. In addition, the magnet was highly radioactive (20 R/hr after six weeks cooldown) further complicating the repair. A shutdown of ten weeks was required to repair the magnet although the actual repair took less than two weeks. This was the first time since the start of IPNS operation in 1981 that an accelerator problem forced a change in the neutron science operating schedule. No experimental time was lost since the lost time was made up by additional running after the repair.

Another problem occurred on April 7, 1985, when after completing the repair of a minor extraction kicker problem, only 50% of the normal beam could be accelerated. Subsequent observations revealed high losses in the fifth short and long straight sections. Vertical aperture measurements indicated a restriction of approximately 15 mm out of a total half vertical aperture of 26 mm. The problem cleared itself for no apparent reason several times, once for a period of two days, but then returned with no hint of clearing again. Background radiation studies in the accelerator tunnel indicated that the problem was in singlet magnet #5. The problem appeared to be a repeat of the incident of May 1983, when several "hoops" of the rf liner in singlet magnet #5 and triplet magnet #6 were damaged by the beam and dropped into the aperture[1]. The accelerator continued operation at reduced current until the next scheduled shutdown. By careful tuning, the accelerator operators were able to restore operation to the 8 μA level. During the shutdown, inspection of the magnet revealed that one of the rf hoops was indeed blocking part of the aperture. Because of the short, one week long, scheduled shutdown, only a temporary repair was made by pushing the hoop back up and reforming into place with a remotely operated pneumatic device inserted into the ring magnet. The repair appears to have worked and a more careful inspection and complete repair will be made during the long summer shutdown.

Recent Improvements

The synchrotron exhibited an intensity dependent high energy instability from its earliest days. It was controlled to the 8-9 μA level by careful dynamic chromaticity adjustment. Above 10 μA this was not by itself sufficient. A combination of two simple techniques has raised the instability threshold above 15 μA. These are discussed in detail in Ref. 3 and will only be briefly discussed here. The instability manifests itself as a beam loss of up to 70% during the last two milliseconds of the acceleration cycle. The intensity threshold at which the loss occurred is roughly proportional to the available rf voltage at $\dot{B}$(max). The cause appears to be a resistive wall instability producing vertical dipole oscillations. One of the solutions is to dilute the beam bunch by modulating the net rf voltage amplitude slightly near the second harmonic of the synchrotoron frequency at $\dot{B}$(max). The other solution requires extraction of the beam 2 ms before B(max), at a time when the $\dot{B}$ is not equal to zero. The peak field is raised to ensure that the energy at extraction remains the same. There is little change in beam energy during the last two milliseconds of the sinusoidal acceleration cycle so it is an ideal time for resonance growth. This technique increases the instability threshold by apparently reducing the allowable resonance growth time.

The accelerator was designed to operate phase-locked to the power mains and only minimal filtering was supplied with some of the power supplies. Therefore, any existing ripple had minimal affect on the accelerator performance since its effect was the same each beam pulse. However, neutron choppers had to be synchronized to the accelerator but could not track the variation of the power main, so the accelerator and choppers were each phase locked to the same stable oscillator.[4,5] This caused the accelerator to slip in phase in respect to the power main and now power supply ripple became a factor. Adding additional filtering on the many power supplies was prohibitively expensive but four major problem areas were identified and feedback loops were designed to minimize the effect of the phase shift.[6] The feedback loops were designed to maintain the stability of 1) the linear accelerator tank rf gradient level, 2) the beam intensity injected into the synchrotron, 3) the injected beam position and 4) the injection field of the synchrotron main ring magnets. These feedback loops have improved the accelerator operators' ability to tune the accelerator for minimum beam losses and maximum intensity without continuously correcting the variations of the previously mentioned parameters. Figure 4 is a plot of weekly averages of time averaged current on target per current of beam loss. The weekly averages begin

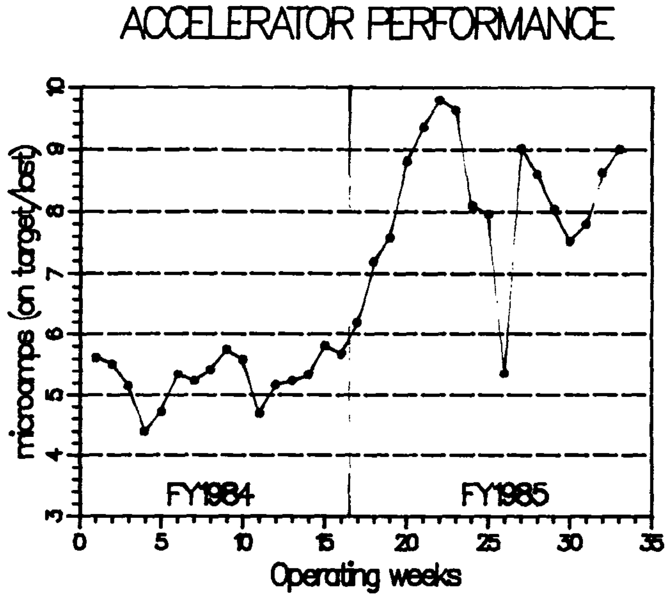

Fig. 4.

in November of 1983, and cover the weeks of neutron chopper synchronized operation through June 1985. It is clearly evident that the accelerator performance improved significantly shortly after the feedback loops were installed at the end fiscal year 1984 (FY1984). The decrease shown for week number 26 was caused by the aperture restriction described earlier. The operators are looking forward to neutron chopper system improvements[7] which will allow the choppers to track the variation of the power main.

Remotely adjustable vertical collimators have been installed in one of the synchrotron straight sections. Their primary objective is to protect the rf liner from further damage after the initial May 1983 failures. Unfortunately, they did not prevent the more recent damage to the liners described in the previous section. They have also been used as diagnostic devices to study the vertical beam size. These studies will be described later.

A recent improvement to the extraction kicker system has not affected the beam intensity, but has improved the system reliability and therefore accelerator availability. One recurring problem with the kicker system had been the interconnecting cables between the magnet coils and the terminating resistive loads. The major source of problem was the termination of the cable itself which was prone to high voltage breakdown failures after about 30 million pulses. The system manager for the kicker system devised a new terminating load, making use of the existing load components, which mounted directly on the magnet coil and eliminated the troublesome cable terminations. This new improvement has significantly reduced kicker system failures as Fig. 3 shows. In addition, several suggestions from the engineers of the thyratron switch manufacturer, English Electric Valve, Ltd., have extended the useful life of the thyratron switches. In fact, one of the four has now operated reliably for over 500 million pulses.

Ongoing Studies

H^- Stripping Foil

The problems with the stripping foils that have been described in the past have not been completely resolved. The standard plastic stripping foils with a thin deposit of aluminum have been used since the start of the accelerator operation. However, the foil lifetimes are not consistent, with some foils lasting tens of millions of pulses and others, only a million or so. Since the normal conditioning of the foils requires operation at reduced intensity for approximately six hours, this reduces the average current. In an attempt to reduce this impact, studies are continuing with other types of stripping foils. Through the cooperation of the SNS staff, several of their aluminum oxide foils had been hand carried to IPNS. Unfortunately, the foils did not fare well during the trans-Atlantic flight and arrived slightly damaged. Enough were salvaged to run some tests and even though the stripping efficiency and scattering effects were good, the oxide foils lasted less than 1 million pulses. Clearly the test was inconclusive due to the less than perfect condition of the foils. Plastic foils with other metal coatings have not improved foil life. A significant step forward has been made with the use of pure carbon foils. These foils have a density of 60 $\mu g/cm^2$ and have been very difficult to mount with one edge of the foil unsupported. A technique has been developed to mount these foils, but with a reduced usable foil aperture. The initial attempts with the carbon foils are very promising with good stripping efficiency, minimal scattering and minimum foil lifetimes of 20 million pulses. The reduced foil aperture did affect accelerator performance somewhat since some of the recirculating beam struck the foil holder. Mounting techniques have since been improved to allow for larger apertures. It is hoped that once the mounting technique has been completely developed, minimum conditioning time will be required with these carbon foils.

Vertical Aperture

Measurements of beam size during capture in the synchrotron using the remotely controlled vertical collimators have shown that at 50 MeV the vertical midplane of the beam is 5 mm above the physical center of the aperture.

Studies conducted with the injection segmented Faraday cups have also shown that the first three injection orbits are also high in those two regions by the same amount. This has raised speculation that if the beam is indeed above the vertical midplane, this could be the cause of the problems with the rf liners. Some additional confirmation of this is a discoloration visible on the liners around the synchrotron above the beam plane, but none visible on the liners below. However, after the rf liner failure in 1983, the upper collimator was positioned within 0.5 mm of the beam to protect the liner. Loss monitor signals indicate that this does protect the liner in triplet magnet #6, but it failed in singlet magnet #5, bringing up the possibility of the existance of vertical orbit warps. Vertical position signals do not show any warps once the beam is bunched, but the possibility of warps during the first 200 turns before the beam is bunched cannot be neglected. The loss monitors, which cannot discriminate between horizontal and vertical losses, do not provide any clues. Studies are planned to investigate this further.

Synchrotron Working Point

During the early days of synchrotron operation, the relatively low intensities did not require working point corrections. Two sets of trim quadrupoles had been provided, but were not used. In an early attempt at eliminating beam instabilities, one of the quadrupole sets was replaced with octupole correction magnets. These magnets were unsuccessful at eliminating the instabilities and are not used. The present higher intensity operation requires the operation of the trim quadrupoles to shift the working point. This correction is provided by the single set of magnets. Computer simulation of the effect on the vertical β function of applying the correction at only one location in the synchrotron lattice indicates the possibility of severe distortions; strangely however, not in the areas where the liner damage has occurred. Nonetheless, the other set of quadrupoles will be installed in place of the octupoles during the summer shutdown. The computer studies indicate that this will reduce the distortion in five out of six locations where the vertical β function reaches a maximum. During the working point studies, another effect became apparent. When the current in the upstream vertical trim quadrupole was reversed to lower the vertical tune, the beam capture efficiency decreased; however, the beam losses during the latter half of the cycle were reduced. Further studies are being conducted, and power supply modifications are underway to dynamically reverse the trim quadrupole currents.

Planned Improvements

Beam Loss Monitoring

The new beam loss monitoring system has become very useful at the present level of operation. However, the day to day variation of these signals is subtle and makes it difficult to determine trends and anticipate potential problems. A new system is being constructed to allow computer sampling of all the loss monitors throughout the acceleration cycle and storing hourly averages of the losses in the control computer memory. The system will allow varied manipulation of the data sets to permit comparisons of the loss patterns on a hourly, daily, weekly and operating cycle basis. In addition, the recording and plotting of vacuum readings by the control computer from 7 locations in the synchrotron and 6 locations in the beam lines has been completed. Since beam losses and vacuum readings are closely linked, the vacuum plots have proved invaluable together with the loss monitor signals for monitoring accelerator performance.

Improved Data Acquisition

A CAMAC based data acquisition system, installed in 1981, is used for monitoring the proton transport system to the target as well as the target parameters. It has operated extremely reliably and provides some very useful additions. One is the ability to notify the accelerator operators of variation in any of the parameters in the data base. The injector and synchrotron data acquisition system does not have this capability, and it is one that is sorely needed. This system is being upgraded to allow this flexibility.

Conclusion

The IPNS Accelerator System has maintained continuous improvement of its operating performance under the difficult conditions of a busy operating schedule and tightly constrained budget. Most of the programmatic resources have gone toward improvement in the scattering instruments and to low temperature moderators. Budgetary limitations have prevented the implementation of most of the long-term improvements mentioned in the ICANS-VII report, most notably, the planned replacement of the ring magnet tuning choke, construction and installation of a third rf accelerating cavity and construction and installation of horizontal and vertical trim dipoles. The Accelerator Operations Group has tried to make improvements in other, less expensive, ways. The records show that it has been successful.

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