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Improvements in the Rapid Cycling Synchrotron*

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Abstract

The Rapid Cycling Synchrotron[1] (RCS), originally designed as an injection energy booster for the Zero Gradient Synchrotron (ZGS), operated under constraints imposed by ZGS operation until December 1979. Once these restraints were removed, the RCS made rapid strides toward its near-term goals of 8 μA of protons for Argonne National Laboratory's (ANL) Intense Pulsed Neutron Source (IPNS) program. Reliable 30 Hz operation was achieved in the spring of 1980 with beams as high as 2×10^{12} protons per pulse and weekly average intensities of over 6 μA on target. These gains resulted from better injection matching, more efficient RF turn-on and dynamic chromaticity control. A high intensity small diameter synchrotron, such as the RCS, has special problems with loss control which dictate prudence during intensity improvement activities. Additional improvements were made to the machine starting in August of 1980 while the extraction magnets were relocated for operation with the IPNS-I target. These improvements have now been completed. Startup of the accelerator is now underway, and it is clear that these modifications have resulted in a radioactively cleaner operation. It is too early to evaluate the effects of the improvements on intensity and reliability, but a single pulse extracted intensity of 2.4×10^{12} protons has been achieved, a 20% increase. The studies and equipment leading to the intensity gains are discussed.

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Introduction

Figure 1 shows the configuration of the IPNS-I spallation neutron facility.[2] It will come into operation in July of 1981 as a national user-oriented facility intended to be used for neutron scattering studies 75% of the time and radiation effect studies 25% of the time. A high energy physics test beam is also provided. In this facility, a fast burst (90 ns) of 500 MeV protons from the RCS is slammed into a uranium target 30 times per second. Resulting spallation and fission neutrons travel down 12 neutron beam lines to users' instruments. A prototype target (ZING-P'), Fig. 1, was the recipient of the protons in 1979 and 1980. The neutrons from ZING-P' were used for target yield studies, moderator material and arrangement studies as well as neutron science. Some 55 publishable neutron scattering measurements were made after the RCS came into a production mode in the summer of 1980.

The trials of turning-on and improving a new machine with scientific users waiting with high expectations is old hat to most of the readers. Normally, however, the users have some previous accelerator user experience and are, therefore, somewhat tolerant of the foibles of synchrotrons. In the case of the RCS, however, the users are reactor oriented and become somewhat irate when the published intensity, energy, and reliability are not available within a few months after startup. Fortunately, the accelerator made dramatic progress in intensity and reliability during the summer 1980 run and the needed rapport was developed between users and operators, and a viable scientific program seems to be on the horizon.

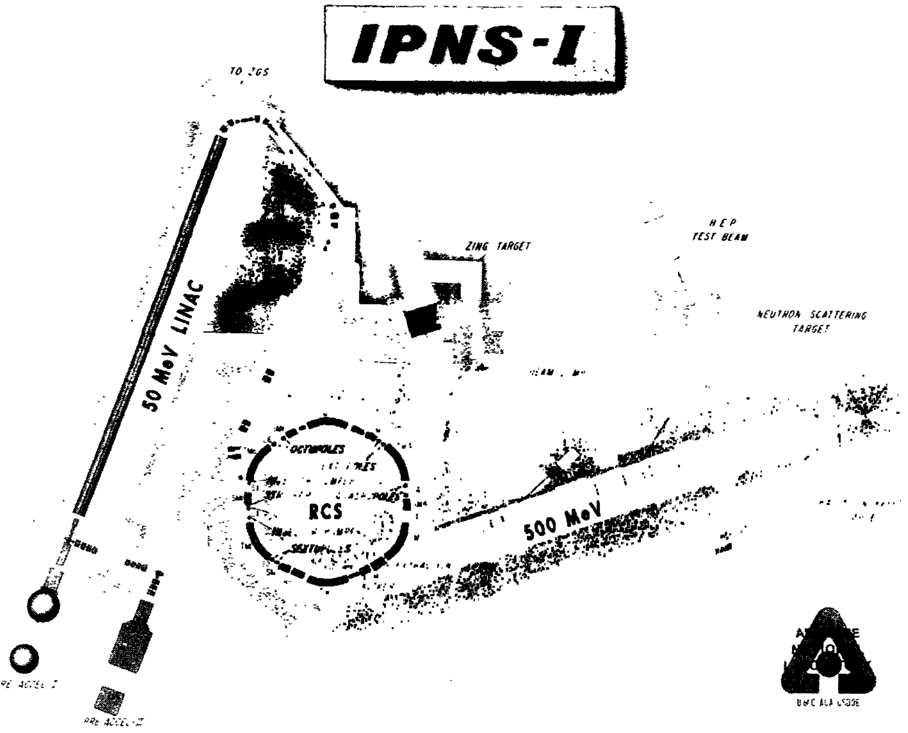

Fig. 1. IPNS-I Accelerator System

The goals of the RCS have long been to deliver 20 μA of 500 MeV protons to a target with 90% operating reliability. Numerous review panels have not seriously questioned the ability of the RCS to meet the 20 μA goal. Neutron science reviews have, however, questioned whether the national neutron science budget can support a dedicated facility like IPNS-I. This is a complicated, many-faceted question which may take quite awhile to answer. Lower goals are compatible with a lower budget and the goals have now been changed to 8 to 10 μA. As Table I indicates, the RCS has made tremendous progress since 1978 and the new lower goals will be achieved in 1981.

Table I

	1978	1979	1980
Scheduled Operating Time	2681 hours	3976 hours	2569.2 hours
Actual Operating Time	1796 hours	2928 hours	2187.8 hours
Operating Efficiency	67%	73.6%	85.2%
Total Protons on Target	0.294×10^{20}	1.06×10^{20}	2.25×10^{20}
Total Pulses on Target	0.43×10^{8}	1.13×10^{8}	1.98×10^{8}
Average Beam Current	0.73 μA	1.61 μA	4.72 μA

The remainder of this paper will present, in chronological order, what improvements were made to achieve these results. It is of great importance to realize that in some of 1979 and most of 1980, the beam intensity was limited somewhat by fears concerning heating and thermal cycling of the prototype uranium target. One certainly must not be fooled into thinking that the target was the only limit. The operators of a small radius fast-cycling synchrotron, without extensively prepared remote handling apparatus, must always consider beam loss control as a prime goal if the synchrotron is to be kept repairable. The gentle positive slope of the beam current vs. time in Fig. 2 was planned as accelerator problems and uranium target worries were slowly worked out in unison. Some of the peak numbers such as 10 μA and 2.4×10^{12} protons per pulse were short-term accomplishments that could not be sustained over long periods because of beam losses, but they do provide input as to the synchrotron's overall capability.

Operation in 1979

The RCS time-shared the 50 MeV linac with the ZGS, usually in a mode of 3 seconds RCS to 1 second ZGS. Programmable bending and focussing magnets made the ZGS H^+ polarized proton operation and the H^- operation of the linac compatible. The operating frequency of the RCS was limited to 15 Hz due to possible damage to the linac when operated at 30 Hz. No one expected major damage, but even two or three weeks of lost operation was considered vital to the high energy polarized beam which was shutting down permanently at ANL in October.

This was a very productive period for the RCS physicists. Approximately 20 hours per week were dedicated to machine studies. Many of the

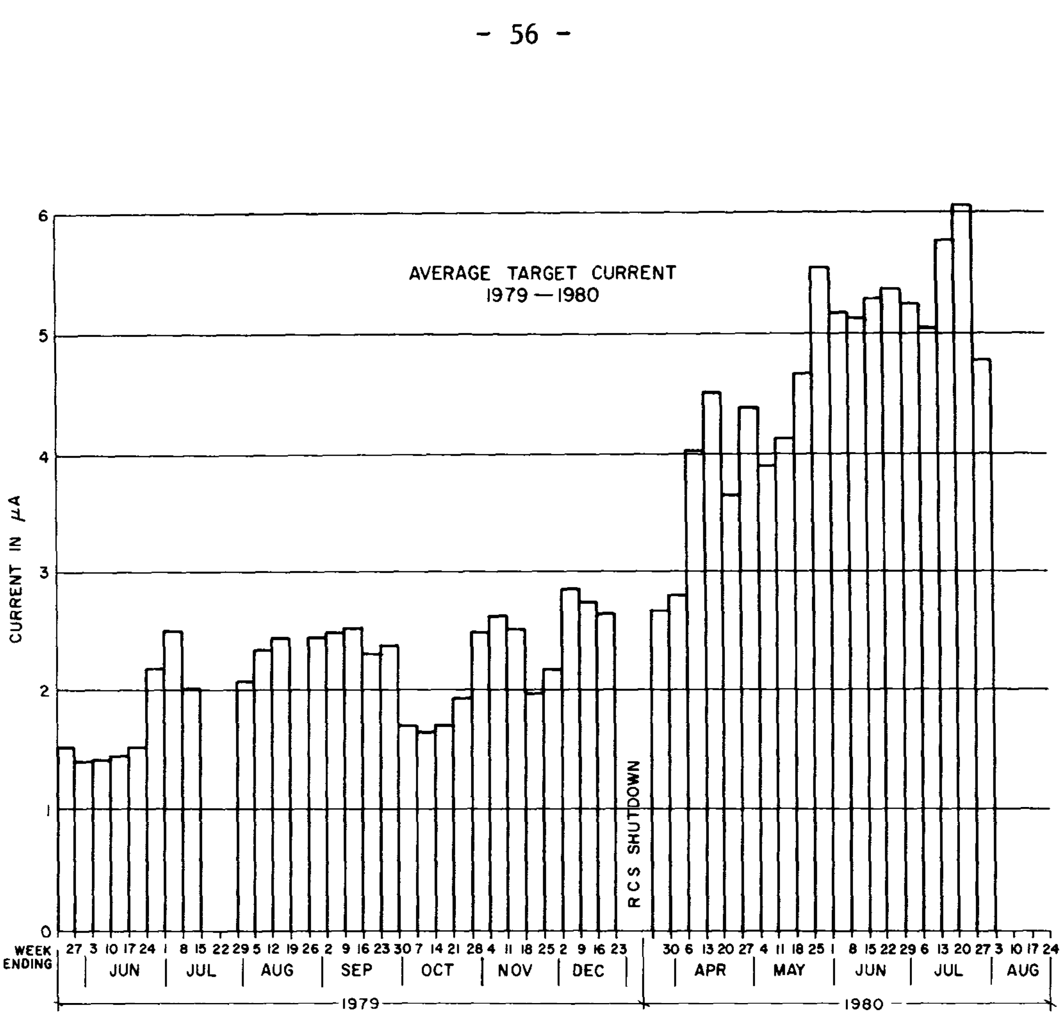

Fig. 2. Weekly Average Beam Current on Target

beam problems uncovered during this period are still being addressed although some were corrected in the spring of 1980 with gratifying results. Studies found that the 500 MeV beam was too large for efficient extraction due to "head-tail" instability.[3] Tune measurements disclosed dynamic reversal of the chromaticity at 350 MeV. Extraction was studied at 200 MeV, and it was noted that 100% of the accelerated beam could be extracted. The extraction kick was insufficient to kick out the wide 500 MeV beam created by the "head-tail" instability. The 500 MeV extraction efficiency was about 65%. A temporary compromise of 300 MeV operation was chosen to get fairly good neutron yield while still providing a radioactively clean extraction efficiency of over 90%.

High radiation levels were detected at the 50 MeV end of the linac. This resulted from gas stripped H^o and H^+ particles. Appropriate shielding was added. Quantitative measurements were made later of H^o and H^+ production as a function of linac tank pressure.[4] These measurements show that H^o and H^+ production is proportional to residual gas pressure as expected.

This was a beneficial time for the users also as neutron yield measurements were made in tungsten, tantalum, and uranium targets. The results agreed fairly well with computer predictions, and uranium was chosen as the target material in the IPNS-I monolith for neutron scattering and radiation damage work. Tantalum backup targets were also built. A uranium target was then installed in the ZING-P' monolith for operation until August of 1980. While this target was only a few pounds of uranium, numerous safety reviews, ad hoc committees, and some 30 target interlocks gave the accelerator operators some new concerns.

One of the more ambitious accomplishments was phase locking the accelerator to a crystal controlled neutron chopper.[5] From the accelerator standpoint this is like the "tail wagging the dog," but it works! Extensive modifications were made in the controls and capacitor bank of the ring magnet power supply of the synchrotron to automatically keep the parallel tuned portion of the system in resonance as the chopper clock forced the system slightly off the power main's frequency. This kept the magnet field stable as it drifted in respect to the power line frequency. An added modification allowed the chopper to control the extraction time of the beam as early as 100 μs before the peak energy and as late as 100 μs after. If the chopper did not call for extraction by the later time, the beam was extracted for the benefit of the other users while the chopper missed that particular pulse. It was found that the chopper and machine were synched within this 200 μs window over 95% of the time. The size of the 200 μs window was chosen experimentally by studying extraction and transport losses for off-nominal energy extraction.

Reliability during this period was not good. The pulsed septum magnet was the real Achilles' heel. It was a 30-inch long conventional 4-turn thin septum magnet. Several different versions of this magnet failed with the best lasting 10^8 pulses. Failure required a lengthy cooldown before repair. The extraction kicker magnet system provided more than its share of failures through high voltage cable breakdowns which often destroyed low level electronics as well.

Once the ZGS was shut down in October of 1979 restrictions on linac operating frequency were lifted, but insufficient data existed to begin 30 Hz operation at once. The ZGS authorities graciously allowed use of half the ZGS main ring magnet system and its beam diagnostics as a spectrometer for analysis of behavior in the linac beam running at 30 Hz. At the same time the linac tank was instrumented for temperature measurements at various points. When the linac was run at 30 Hz with RF on for long enough to accommodate 120 μs beam pulses, some hot spots were noted on uncooled tuning balls. These had grown leaky over the years and the water was shut off, which was acceptable during low power operation. A very clever design provided cooling for these leaky units, but construction and installation of these cooling adapters took over two months. Thirty-hertz operation was tried again in mid-December, but because of kicker magnet power supply problems it was not successful, although short-term currents of 5 μA were achieved.

1980 Modification and Operation

From January until the third week of March the machine was off for improvement. The most extensive was the installation of a new transformer septum magnet[6] that provided one-half the bend of the old magnet. A more standard dc septum provided the remainder. In addition, two small vertical and one small horizontal trimming magnets were designed and built to better

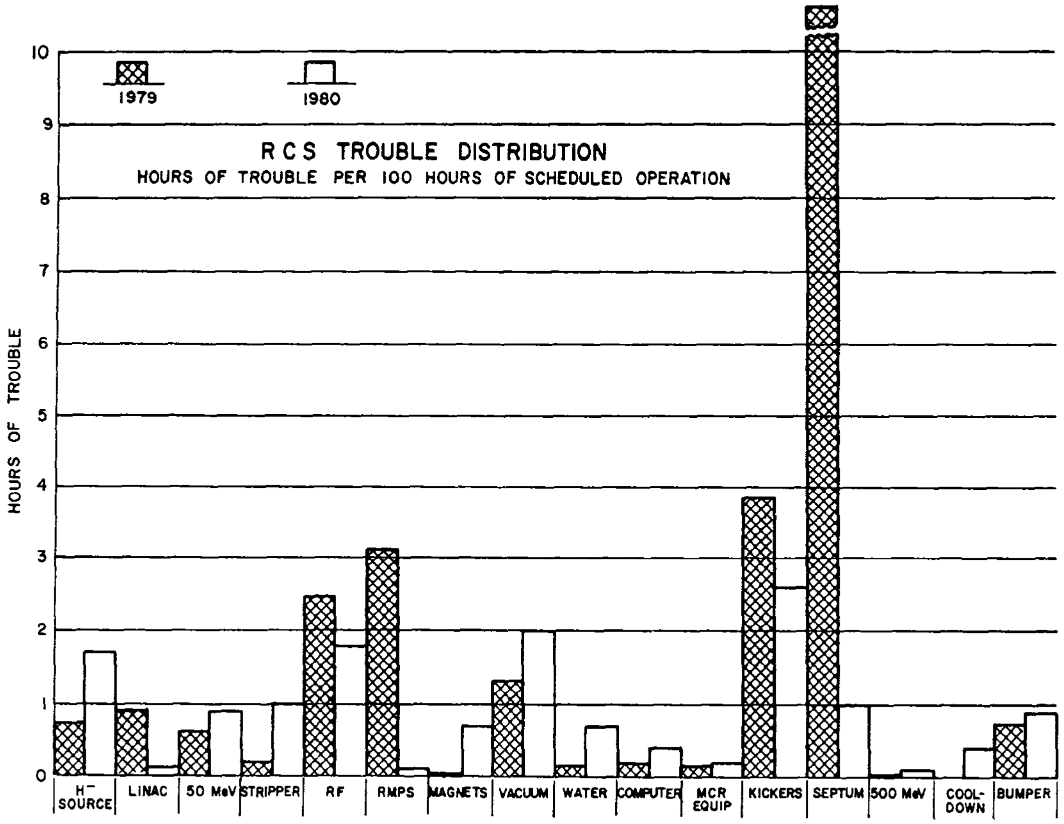

Fig. 3. Comparison of RCS Trouble Distribution for 1979 and 1980

match the machine to the target transport line. Significant improvements were made in protecting the low level electronics in the kicker magnet power supplies, and cable termination problems were solved. These two efforts made great improvements in the operating reliability of these systems, as can be seen from comparing the 1979 and 1980 system reliability data in Fig. 3. Several other modifications were added to improve beam output and beam handling efficiency. Programmable linear amplifier power supplies were provided for dynamic chromaticity adjustment. Preamplifier improvements were made in the RF system to improve dynamic range and automatic gain control (AGC) response. Ninety percent of the complicated 50 MeV transport line from the linac to synchrotron was wire orbitted, and the beam diagnostics were realigned for better injection matching. A 750 keV proton beam chopper was constructed to give the machine synchronous injection capability. One look at Fig. 2 from April through July 1980 should convince the reader that these modifications were, on the whole, quite successful. It was during this running period that 30 Hz operation became routine. The reader should bear in mind that this running was carried out with the ratio of beam on target to 50 MeV beam delivered to the synchrotron at 70% or better.

Machine physics studies continued during this running period, more problems noted, some corrections made and some longer range plans formulated. A disturbing coupling between proton beam noise and the ring magnet power supply was discovered and partially corrected. This was particularly troublesome when the accelerator was running in synchronism with a neutron beam chopper. Two-turn extraction, 500 MeV acceleration, and the effects of space charge distribution were among the more common topics. The most troublesome aspect of beam acceleration was, and remains, an instability which occurs at intensities of over 1.5×10^{12} protons per pulse for about the last 6 ms of the acceleration cycle. It seems to be longitudinal in nature since there is a great deal of bucket size modulation. A "head-tail" instability has been noted at this time in the acceleration cycle. This instability causes about 3% amplitude modulation in the RF amplitude envelope. Several theories have been considered concerning this instability: (1) Oscillation in the AGC loops of the RF system; (2) Oscillations in the loop that phase locks the two RF cavities together; (3) Coupling between the dc position feedback loop and the band-pass beam phase compensation loop; (4) A microwave instability generated by beam coupling to the eddy current shields in the accelerator; (5) A microwave instability caused by the lack of symmetry in the straight sections. This instability has been controlled during 300 MeV operation with extracted beams up to 2.4×10^{12} protons by very judicious injection and careful chromaticity adjustment, but it cannot be said to be operational at 30 Hz at these intensities due to extensive beam losses.

Conversion for Operation into IPNS-I Target Monolith

The accelerator was shut down August 4, 1980, to begin the attachment of a new proton transport system (PTS) to carry the beam to the IPNS-I target monolith. From the accelerator standpoint, additional work was required as may be seen in Fig. 4. The extraction straight section containing the septum magnets has been moved from the L-4 to L-3 straight section; a set of quadrupoles was moved from the L-3 to L-4 straight section; a longer fast kicker magnet has been installed in the S-3 straight section; extensive shielding additions totaling 450 tons of concrete have been added over the extraction straight section.

Several system modifications and additions were completed during the time of IPNS-I conversion. These items should improve beam handling, beam intensity and operating reliability. The most ambitious of these has been complete reconstruction of the fast kicker extraction system. A new magnet and power supply[7] have been designed and constructed to provide efficient 500 MeV extraction. Four separate thyratron switching power supplies each drive 1/4 turn of a 75 cm long ferrite magnet. Each 1/4 turn is terminated in 7 Ω and the system is operated at 62 kV. The peak switched power is over 0.5 gigawatts. The four supplies must fire within 2 ns of each other. So far, the system works quite well. Measurements with the proton beam indicate the kick angles are as predicted.

Octupole magnets[8] driven by programmable 30 kW linear transistor amplifiers have been added to the synchrotron. Betatron tune measurements indicate that these magnets perform as predicted; however, they have not as yet shown the ability to control beam instabilities. Less than four hours of machine time has been spent in applying them to instability correction studies, so prospects for their success are still bright. The injection bumper power supply was modified extensively to up its duty

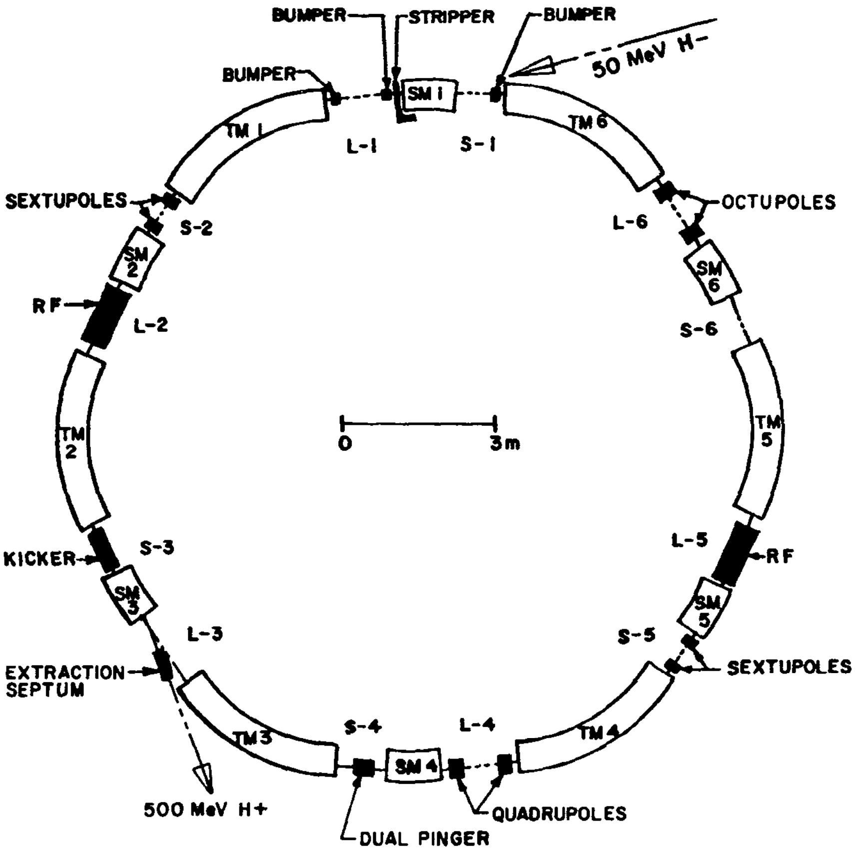

Fig. 4. RCS Component Arrangement

cycle by 50%, provide faster injection slewing and greater waveform flexibility, as well as improved accessibility for repair.

Linear transistor amplifiers control the dynamic impedance of the RF cavities by magnetically modulating the inductance as the RF frequency sweeps from 2 to 5 MHz during the beam acceleration cycle. These amplifiers are part of the cavity bias system (CBS). New CBS amplifiers have been constructed and installed which increase the corner frequency of this system from 800 Hz to 10 kHz. It is hoped that better cavity impedance control will improve many aspects of the dynamic RF performance, in particular, better cavity-to-cavity tracking and better AGC control, since both the phase and magnitude of the load impedance seen by the amplifier are more constant. The synchrotron oscillation frequency of the beam varies from 4 to 7 kHz during the machine cycle. The potential problem of having the CBS response span this frequency was recognized. In fact, studies have shown that beam losses do increase when CBS response corners above 3 kHz, so the response is limited there.

Extensive changes have been completed on the RCS computer control system with an Eclipse AP-130 replacing a NOVA 210. The greatly augmented capacity is used to interact with machine studies,[9] provide more flexible parameter monitoring and readout to control and monitor the new proton transport line to the IPNS-I target. It also monitors all the parameters required for cooling and radioactivity control of both the neutron scattering and radiation effect targets and is part of the protective shutdown system.

The accelerator physics team remeasured both the injection and extraction orbits during the IPNS-I installation shutdown. They recommended changes in nominal injection angle and extraction apertures. These changes were carried out with what seems, at this time, to be excellent results. Beam output to input ratios have improved from 70% to 85%. Radiation outside shielded areas has decreased by factors of at least 5 and in some places by a factor as high as 20. Of course, shielding improvements and improved extraction kick have also helped.

Linac and Ion Source

One does not expect that a 1 Hz linac and a 1 Hz H^- ion source will easily operate at 30 Hz, but they have performed suprisingly well. The linac, with the beam pulse width restricted to 70 μs or less, has performed flawlessly thus far. Modifications in tank water flow, tuning ball cooling and oscillator cavity cooling have been necessary. The ion source, with similar power restrictions, has done well with grid life being the limiting factor. With pulse widths under 60 μs, grids last about six weeks.

The previously mentioned fiscal problem has brought a two-year program of ion source development to a halt. A Penning discharge type H^- ion source was beginning to show promise.[10] This work has completely stopped. Linac operating personnel are working to adapt a 15 Hz magnetron type source to 30 Hz operation. This will be a very modestly financed program and does not have a high probability of success for that reason. A new or improved ion source is generally regarded as one of the easiest ways to improve RCS beam intensity.

Foil Life

The stripping foils used in the RCS are made of poly-paraxylene.[11] They are 3000 to 4500 Å (60 $\mu g/cm^2$) thick with a 400 Å coating of aluminum deposited on them. Considerable work has been done on nonstressed mounting of these foils with satisfying results, but the aluminum coating has been the most effective factor in extending their life to millions of beam pulses. The aluminum coating allows a bleed-off of charge and also allows for an even distribution of charge. Noncoated foils tend to contract when protons pass through them.

The injected current on the RCS is typically 5 mA for 60 μs. The way this beam is injected determines the number of passes the recirculating beam makes through a foil. This obviously has a significant, but unquantified, effect on foil life. The RCS has a remotely controlled foil changer which can hold 50 foils in its magazine. For reasons that are unclear, a new foil survives best if it is "conditioned" for an hour or so at 5 Hz before applying beam at 30 Hz. Foils usually last about 10 million pulses.

Conclusions

Great strides have been made since the 1978 commissioning. Weekly average beam currents have gone from less than 1 μA to over 6 μA, weeks with over 15 million extracted pulses have been recorded and reliability has jumped from 67% to 85%. Peak intensities of 2.4 x 10^{12} protons per pulse and a 24-hour average of 7.6 μA has been attained. Much remains to be done. Five-hundred MeV operation must be reliably demonstrated. Firm control of beam losses must be maintained and stable financing would help.

Acknowledgments

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