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INTENSE PULSED NEUTRON SOURCE ACCELERATOR STATUS*

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Introduction

The Intense Pulsed Neutron Source (IPNS) facility has been in operation since November 1, 1981. From that date through August 1, 1983, the accelerator system was scheduled for 7191 hours of operation. During this period, 627 million pulses totaling about 1.1×10^{21} protons were delivered to the spallation target. The accelerator has exceeded goals set in 1981 by averaging 8.65 μA over this two year period. This average beam current, while modest by the standards of proposed machines, makes the IPNS synchrotron (Rapid Cycling Synchrotron [RCS]) the highest intensity proton synchrotron in the world today. Table I, Figs. 1 and 2 provide more detailed data on accelerator operation. Weekly average currents of 12 μA have been achieved along with peaks of 13.9 μA. A great deal has been learned about the required operating constraints during high beam current operation. It should be possible to increase the average beam current during this next year to 12 μA while observing these restraints. Improvement plans have been formulated to increase the beam current to 16 μA over the next three years.

Operating Summary - General

The original IPNS accelerator system has been previously described in detail elsewhere.[1,2] Extensive modifications[3] to the base system were made in 1980 and 1981. As Fig. 1 implies, with these modifications in place, it was a reasonably straightforward activity to get the accelerator currents up to the 8 μA short-term goal. The H^- ion source in operation at that time could deliver a charge of only 8×10^{12} ions 30 times per second. When the various transport and acceleration efficiencies were considered, a time average of only 10.0 μA of 50 MeV H^- ions could routinely be delivered to the synchrotron for acceleration to full energy. This was, in a way, fortunate since it encouraged us to make the beam handling more efficient and put a greater premium on reliability. We were able to limit average beam losses to only about 4×10^{11} protons/pulse and maintained a combined acceleration and extraction efficiency of about 85% in the synchrotron. The residual radiation level in the synchrotron tunnel stayed reasonably low, with only 4 locations reading greater than 300 mrem after a 4 day shutdown. In fact, maintenance personnel were exposed to a total of only 7.55 man-rem of radiation in 1982.

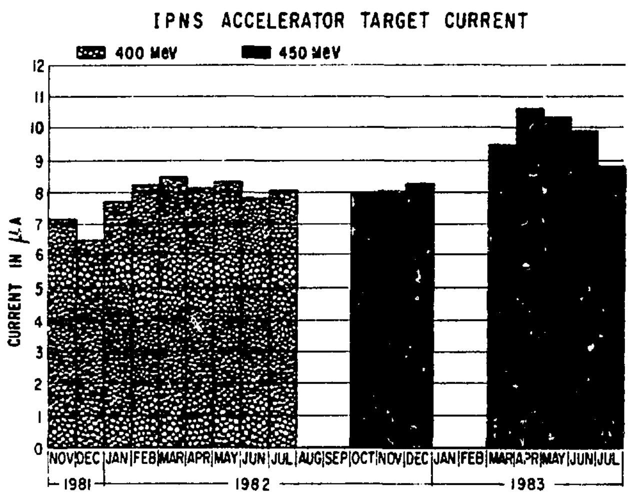

Fig. 1. IPNS Accelerator average target current.

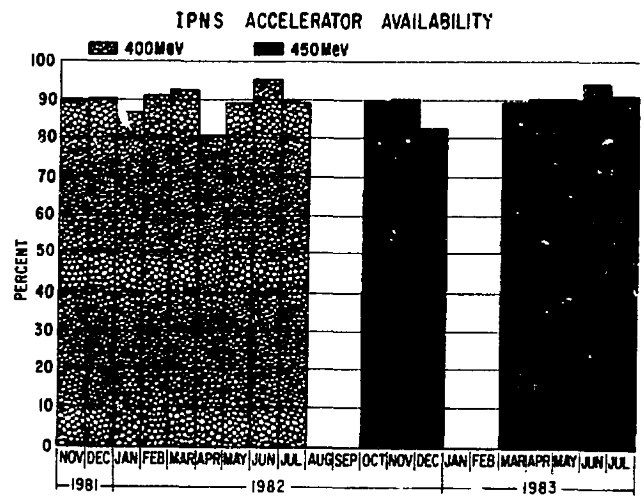

Fig. 2. IPNS accelerator availability since turn-on.

Table I.

Accelerator Operating Summary

	Nov. 1981-July 1982	Oct. 1982-July 1983
Proton beam energy	400 MeV	450 MeV
Average beam current	8.02 μA	9.21 μA
Operating efficiency	88.9%	90.2%
Scheduled operating time	3358 hours	3833 hours
Available operating time	2985 hours	3458 hours
Total pulses on target	2.94×10^8	3.33×10^8
Total protons on target	4.44×10^{20}	6.39×10^{20}

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In March of 1983, a more intense H^- ion source became operational and the beam current became limited by the losses that could be tolerated in the RCS tunnel. The 12 µA beam current noted above was achieved with loss of 5.5×10^{11} protons per pulse. We feel this is about the maximum long-term average beam loss that can be tolerated and still allow for hands-on maintenance. The RCS tunnel has a mean diameter of 50 feet, a width of 7.5 feet and a mean height of 8 feet, so little room is available for temporary shielding, special handling fixtures, etc. Future higher intensities can only be achieved by more efficient beam capture and acceleration.

Automatic devices are set to shutdown the beam when the losses exceed an average of 7.5×10^{11} for one second. When the machine is operating at 30 Hz at 5.5×10^{11} loss (normal conditions), a slight power supply current change or beam instability will easily cause a beam shutdown. While restart is simple, some neutrons are lost and an undesirable target thermal cycle has occurred. The IPNS accelerator is, therefore, a machine that has to be "tuned" very deliberately. This means that the trial and error tuning that usually produces the highest accelerator current is difficult if not impossible on this accelerator. Power supply instability due to phase slip with respect to the power line phase (when the accelerator is synchronized to a neutron chopper) and a pesky high energy longitudinal beam instability have been previously described.[3] Substantial improvement has been made in these two operating problems, but they are not totally cured. These two effects keep the accelerator system on the verge of a beam shutdown at all times when maximum proton currents are required.

The Preaccelerator and H^- Ion Source

The H^- ion source in use at start-up in 1981 used double charge exchange to produce the low energy H^- ion beam. This source was quite reliable but was limited to a current of 20 mA (on good days!). To reach planned future goals of the accelerator system, at least 40 mA of H^- was required. Earlier Argonne studies of a Penning H^- ion source[4] were somewhat discouraging due to unreliability and high hydrogen gas flow requirement. A magnetron H^- ion source developed at Fermi National Accelerator Laboratory (FNAL)[5] has worked reliably for several years. With the standard FNAL magnetron source, sufficient beam could be obtained but the pulse width was limited by excess cathode temperature to 30 µs at a 30 Hz rate. The high arc current required (120-150 A) tended to overheat the cathode. By incorporating a focusing groove in the source cathode, the required arc current decreased to 40 A. The focusing groove technique was discovered at Brookhaven National Laboratory (BNL).[6]

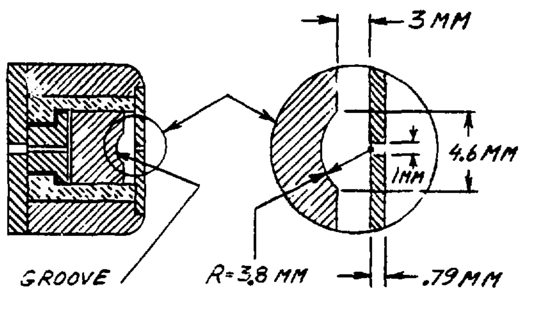

Fig. 3. Magnetron H^- ion source with grooved cathode.

The new IPNS source[7] can produce a 50 mA, 70 µs wide pulse at 30 Hz with the cathode temperature reaching only ~370°C. The grooved cathode also produces a more stable arc with less low frequency noise. The lower arc currents also require less hydrogen flow to maintain a discharge. A cross section of the magnetron with a groove in the cathode is show in Fig. 3.

In the IPNS preaccelerator an extended transport line is required to connect the source into the preaccelerator high voltage column. Space charge neutralization is required to prevent blowup in this transport line. A flow of ~0.2 atmospheric cm^3/min of dry nitrogen seems to be adequate. Good neutralization requires about 30 µs of mixing time. This early portion of the beam pulse is chopped out before it reaches the linac by a 750 kV traveling wave beam chopper.[8] This chopper is also used in the safety system to enable the source to continue to operate at constant temperature when operating requirements dictate no beam, a change in pulse width or a change in repetition rate.

The performance of the new ion source has been excellent. During a total running time of 3100 hours, in that period only one two-hour unscheduled source shutdown occurred and this resulted from an ancillary power supply problem. The source body was opened and inspected after a 5 month period. It took less than 2 man-days to clean the source up and get it operational again. We feel the lower temperature operation is responsible for the long operating life and lack of internal damage.

The ion source is capable of delivering up to 30 µA of average current to the RCS while only about 15 µA maximum is presently usable in the synchrotron. It is thus possible to run the preaccelerator voltage and linac RF levels lower to improve reliability since maximum beam transport efficiency from the preaccelerator to the RCS is not required. We have recently added feedback circuits to exactly regulate the amount of beam delivered to the synchrotron each pulse. This helps to control the number of excess beam loss trips since we operate so close to a beam loss trip limit most of the time.

Linac

The linac has now been running for two years with input RF power at 150% of the initial design level. Overall linac reliability has been excellent with breakdowns accounting for 1% of scheduled operating time. The life of the expensive RCA type 7835 final power amplifier tube is equal to that obtained during Zero Gradient Synchrotron (ZGS) operation when average RF power levels were about 3% of present levels. The dc blocking capacitors on the final power amplifier have been the most troublesome component, but when they are properly fabricated 200-300 million pulses can be expected. There has been no appreciable buildup of residual radiation in the linac components.

Rapid Cycling Synchrotron

Reliability and Cost Improvement

The extraction kicker magnet has 4 quarter turn coils each originally designed to be driven by and terminated in 7 Ω. The planned operating voltage of 68 kV proved difficult to handle because of cable breakdowns and corona discharge at connections. Judicious impedance mismatching has reduced the operating voltage to 49 kV without effecting the current pulse rise time or creating harmful reflections. Beam extraction efficiency remained at essentially 100%. The driving point impedance is now 4.67 Ω and the terminating resistors are 6 Ω. The power supply presently contains four $14,000 CX1192 deuterium thyratrons. Originally estimated for a life of 10^8 pulses, the tube life has, in fact, averaged over 3 x 10^8 pulses with these modifications in place. Since 10^8 pulses is only 7 weeks of operation, this is a significant cost saving. The lower required voltage will allow future operation to be conducted with the cheaper CX1175 type tube.

Beam Intensity Improvement

In October of 1982, the beam energy was increased from 400 MeV to 450 MeV without loss of average current. This meant an increase in the neutron per proton ratio of about 18%. The new ion source became operational in March of 1983. Within 2 months, the weekly average current increased from 8 μA to almost 12 μA. Several changes in the synchrotron operating mode made this possible. A change in the injection working point of 0.03 increased the efficient capture intensity from 2.4 to 3.0 x 10^{12}. This required a trim quadrupole current of about 7 A. Sustaining this small tune shift beyond about 5 ms into the cycle actually made high energy operation more unstable.

The threshold of the high energy longitudinal instability that bothered the RCS from its first days was raised in early 1982 from about 1.3 x 10^{12} to 2.4 x 10^{12} protons/pulse by reducing reflections in the low level RF portion of the beam phase feedback system. The increased current from the new source made the problem reappear above 2.4 x 10^{12}. This problem has now been solved again, at least at present intensity, by artifical bunch dilution. Figure 4 shows traces of the high energy longitudinal beam profile with and without bunch dilution. The diluted beam signal (upper) clearly shows a bunch with decreased localized particle density. Following a technique employed at the Japanese National Laboratory for High Energy Physics (KEK)[5], we deliberately inject a controlled amount of noise into the RF master oscillator for about 2 ms starting shortly after $\dot{B}$ maximum. The frequency of this noise is fixed a few % above the beam synchrotron oscillation frequency. Counter phasing the two RF cavities at this noise frequency did not produce the same result as it did at KEK. New equipment is now being installed to allow the noise frequency to linearly track the changing synchrotron frequency in hopes of reducing the longitudinal problem even more.

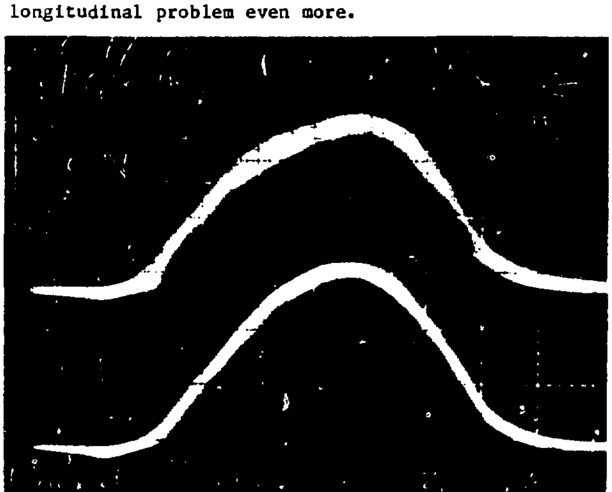

Fig. 4. IPNS beam bunch at 430 MeV.
Upper trace - artifically diluted by synchrotron noise. Lower trace - undiluted.

The higher currents available from the new ion source also made the problem of "beam noise" more acute. These beam generated electrical signals effect numerous low level signals but have been particularly troublesome in the ring magnet power supply where under certain circumstances beam noise causes a ring magnet current change which causes an orbit shift which, in turn, causes greater beam noise, etc. An adverse positive feedback loop thus exists which, over several cycles, will cause beam losses large enough to trip the machine. Extensive efforts at filtering have been at least partially successful. This noise effect was also diminished by installing a circuit to correct the RF capture frequency in proportion dc drifts in the $\dot{B}$ integrator that feeds the RF function generator. All efforts to "clean up" signals by trial and error filtering are severely handicapped in that radiation levels prevent "beam-on" access to troubled equipment.

H^- Stripping Foil

There has been no major effort employed to change the stripping foil material or methods of foil suspension this last year. The brighter ion source allows a pulse narrower in time. The narrow pulse, combined with changed operating modes on the injection bumper magnet have decreased the time that already stripped protons recirculate through the stripping foil. With these techniques operable, a typical well conditioned foil lasts about 1-1/2 weeks (20 million pulses). Techniques to "condition" the foil include a larger than normal injected beam size, exposure of as much of the foil as possible to beam, and a slow buildup of current over about 3 hours. Foils have lasted as long as 55 million pulses with up to 1.5 x 10^{20} ions stripped.

Operating Problems

Little has been done thus far to localize the damaging effects of lost beam. A protective carbon block has been installed just upstream of the kicker magnet vacuum chamber. This protective block has clearly reduced vacuum leak problems in this area. Installation of remotely movable carbon shield blocks has been contemplated in the S-4 straight section for some time. This installation has not been given nearly as much priority as increasing beam intensity.

We have known for some time that the injection bump magnets and some diagnostics show some signs of radiation damage. However, the first serious problem directly attributable to excessive lost beam occurred in late May when the machine was operating at 13 μA. The beam intensity suddenly dropped by a factor of two. After many hours of tests and observation, we determined that the aperture inside ring triplet magnet #6 was partially occluded. Residual radiation readings and brief crude viewing indicated a problem at a point where the vertical beta function reached is maximum. A temporary repair restored 10 μA capability. The accelerator ran a little over two months until August 1 with this restricted condition.

A more detailed inspection in August after a 3 week cooldown revealed that the beam had burned completely through one of the "hoops" of the RF liner. Figure 5 shows the damaged piece protruding slightly into the aperture. We think that when heated by the magnet and beam, the hoop droops further into the aperture. We plan to cut this out with some remotely operated shears during the present shutdown.

A similar damaged hoop was discovered at the entrance to ring singlet magnet #5. This was not at a point of maximum vertical beam size, so its origin is

Fig. 5. Damaged liner of triplet magnet #6. End view with mirror reflected view from bottom.

more puzzling. Vertical orbit distortions may be playing a part in the problem. The alignment will be checked before operation resumes in late September. Problems like this make the operators long for vertical trim dipoles. Carbon scrapers will be installed at one or more points in the ring in an attempt to protect the liners from future problems.

Future Plans

Taking into account both beam current and beam energy changes, the IPNS accelerator is now producing about 80% more neutrons per pulse than it did at the beginning of 1982. We expect to increase the beam energy to 500 MeV in October, which will provide a further 18% increase. The RF liner problem in May forcefully reminded us that we are running a pretty "hot" machine. Despite this, we feel it is possible to increase the average (not peak) current to 16 μA within 3 years.

A plan to accomplish this and provide better long-term viability has been established. This plan includes the following:

1. Construct an additional spare ring magnet of each type.
2. Replace the aging ring magnet tuning choke with a higher inductance choke.
3. Improve beam loss monitoring and loss monitor data logging.
4. Replace single phase apparatus on linac transmitter with three phase.
5. Install 2 (perhaps 4) trim horizontal and vertical dipoles for injection orbit optimization.
6. Install a third RF transmitter with option to run this transmitter on the second harmonic for all or part of the acceleration cycle.
7. Install internal adjustable collimation to protect synchrotron apparatus from missteered beam.

As stated before, the key to successful higher current operation of this accelerator is beam loss control. The items above should help provide better orbit stability, tunable aperture optimization and reduction of the charge density within the aperture—all consistent with beam loss control.

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