BEAM INTENSITY INCREASES AT THE INTENSE PULSED NEUTRON SOURCE ACCELERATOR*

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Summary

The Intense Pulsed Neutron Source (IPNS) accelerator system has managed a 40% increase in time average beam current over the last two years. Currents of up to 15.6 μA (3.25 x 10^{12} protons at 30 Hz) have been successfully accelerated and cleanly extracted. Our high current operation demands low loss beam handling to permit hands-on maintenance. Synchrotron beam handling efficiencies of 90% are routine. A new H^- ion source which was installed in March of 1983 offered the opportunity to get above 8 μA but an instability caused unacceptable losses when attempting to operate at 10 μA and above. Simple techniques to control the instabilities were introduced and have worked well. These techniques are discussed below. Other improvements in the regulation of various power supplies have provided greatly improved low energy orbit stability and contributed substantially to the increased beam current. These improvements are discussed in a paper[1] presented at this conference.

Introduction

The Argonne National Laboratory IPNS accelerator system[2] consists of an H^- ion source, a 50 MeV linac and a 500 MeV 30 Hz synchrotron. The intense extracted proton beams (>12 μA time average, >8 A instantaneous) strike a U-238 target. The proton burst is about 90 ns long and a 1 μs pulse of moderated neutrons is produced. The neutrons are mostly produced by spallation although a fission component exists. The neutrons are directed to a variety of instruments for materials science studies. These instruments and the target facility have been described in other publications.[3] Given the political problems encountered by reactors these days, accelerator based neutron sources seem like the wave of the future in neutron scattering. While IPNS is a small facility, it is a pioneer in this new activity and has gotten quite a bit of user attention. In fact, over the last two years, 134[4] neutron science reports have resulted from IPNS work. Over half of these were in refereed publications. Twenty-seven were invited presentations.

The success of the neutron science program has stirred us to generate some ideas[5] to increase the accelerator beam intensity but the general budgetary limitations experienced by all have prevented our undertaking any costly improvements. Judicious management of our operating funds have permitted us to make a few modifications which have had quite a beneficial effect as shown by Table I. Particularly pleasing is the 40% increase in time average current.

Table I.

	Nov. 1981- July 1983	Oct. 1983- Feb. 1985
Average beam current	8.65 μA	11.90 μA
Scheduled operating time	7191 hours	5567 hours
Available operating time	6443 hours	4973 hours
Pulses on target	6.27 x 10^8	4.91 x 10^8
Total protons on target	1.08 x 10^{21}	1.22 x 10^{21}
Beam energy	400-450 MeV	450-500 MeV

The Instability Problem

The magnetic guide field of the synchrotron varies sinusoidally with time at a fixed 30 Hz repetition rate. Fifty MeV ion injection occurs about 200 μs before B_{min}. Acceleration nominally lasts for 16.66 ms and B_{max} is 8.33 ms after B_{min}. Since first commissioned, the synchrotron has been subject to sudden loss of beam about 2 ms before extraction at B_{max}. The lower trace of Fig. 1 shows the beam intensity versus time with no beam loss. The upper trace shows a loss of about 70% of the beam starting about 1.8 ms before extraction. The signals are derived from a beam toroid. The intensity threshold at which this loss occurred is roughly proportional to the rf voltage amplitude available at B_{max}. The cause of the sudden loss seems to be a resistive wall instability producing vertical dipole oscillations and vertical beam loss. Vertical position signals at a frequency $f = (n \pm 1/4)\, f_o$ show an increase near the end of the acceleration cycle and the losses are associated with a sharp intensity dependent threshold in the amplitude of these oscillations. With the intensities available from the old ion source, this instability was adequately controlled by careful adjustment of injection conditions, phase feedback gains and dynamic chromaticity.

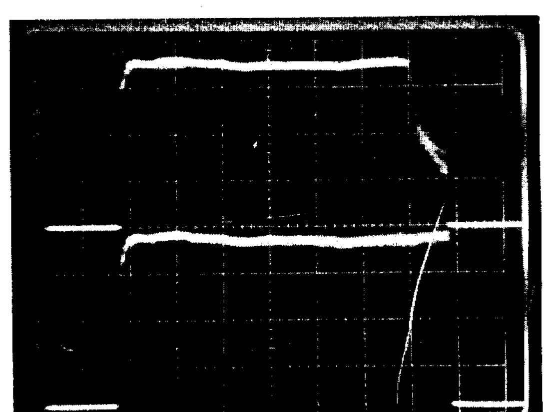

Fig. 1. Upper trace: Beam intensity versus time. Beam loss 1.8 ms before extraction.
Lower trace: Beam intensity versus time. No loss. Extraction at 14.66 ms.

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In March of 1983, an improved H^- ion source[6] became operational. With this ion source feeding the linac, it became possible to deliver more than 20 μA (12 mA for 55 μs at 30 Hz, 4.12×10^{12} per pulse) of 50 MeV H^- ions to the synchrotron. Of course, the synchrotron could not cleanly accelerate such intense beams immediately. In fact, the instability which had been successfully controlled to 8-9 μA intensity levels became a bottleneck in our intensity improvement program. Low energy orbit stability was a problem that also received attention.

Higher rf voltage seemed the most straightforward answer based on our previous experience but funding problems killed our ideas for another cavity and a few thundering cavity arc-downs stopped us from trying to routinely operate at more than 10.5 kV per cavity. Some other solution was required. The Japanese KEK Laboratory had tried a device called a "phase shaker"[7] to get through transition. Our version of a "phase shaker" is called the "scrambler." It controls this instability completely with routine repeatable adjustments up to 14 μA. Above 14 μA the technique works but sometimes takes some patient tuning to set up.

Figure 2 shows the "unscrambled" beam bunch immediately prior to beam loss. The time base is 20 ns per division. Figure 3 shows the "scrambled" beam bunch which does not get lost despite its rather shaggy appearance. The "scrambler" seems to function by reducing the instantaneous current and, therefore, of course, reduces the induced transverse field. These fields are proportional to $Z_\perp \Delta I/2\pi R$, where $Z_\perp$, Δ, I, and R are the perpendicular wall impedance, the perpendicular offset, beam current and accelerator radius, respectively. The perpendicular impedance which has not been measured, presumably has considerable frequency dependence since the vacuum pipe is discontinuous due to acceleration diagnostics and a variety of injection and extraction devices. Increased tune spread due to Landau damping tends to help control the instability if injection conditions are exactly right. Providing additional tune spread with octupoles has been tried and has not been helpful. Active dampers were considered before the "scrambler" solution proved adequate.

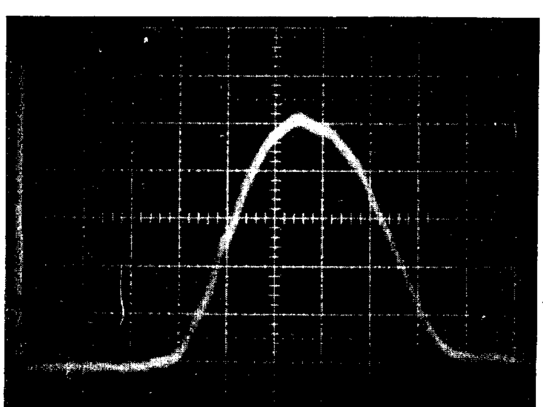

Fig. 2. "Unscrambled" beam bunch just prior to loss.

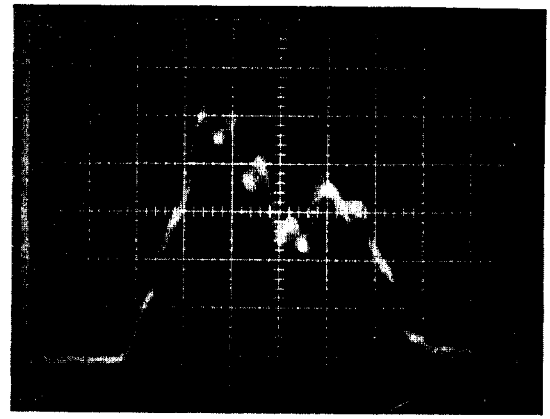

Fig. 3. "Scrambled" beam bunch. Carries to extraction with no loss.

The "scrambler"[8] is a gated oscillator with two available gate intervals. Each interval can start with some initial frequency which can be linearly ramped up or down from the starting point. During the first successful operation of this device, the output modulated the master oscillator (mo) frequency at about a 6 kHz rate. The resultant frequency out of the mo is near the synchrotron sideband of the revolution frequency. This modulation tends to produce coherent synchrotron motion so the frequency, amplitude and duration of this modulation is quite critical. The trick is to dilute the beam bunch without losing many particles in the process. This modulation has also been successfully applied to the cavity to cavity (the IPNS synchrotron has 2 rf cavities) phase lock loop. Controlling the instability by modulating the effective rf voltage amplitude is also consistent with the Japanese experience. Choosing a frequency near the second harmonic of the synchrotron frequency seems to work slightly better in that the instability is controlled with less beam loss.

The "scrambler" operating conditions now most commonly in use are:

1. Turn on at $\dot{B}_{max}$ with a duration of 4 ms. Exponential increase in amplitude at turn-on with a 600 μs time constant. Step function turn-ons lose beam.

2. Modulation of the net rf voltage amplitude seen by the beam. This modulation changes the phase of cavity A with respect to cavity B.

3. The frequency chosen is slightly above the second harmonic of the synchrotron frequency and is ramped to track the changing synchrotron frequency.

Overdriving the "scrambler" can produce beam loss and it can also produce a cyclic modulation of the bunch size for up to 3 milliseconds after the scrambler is shut off. This produces pulse to pulse variation of the beam bunch length at extraction. Variable transport losses and beam motion on the neutron production target result.

Early Extraction

Another technique that has worked successfully to ease control of this instability is what we call "early extraction." The nominal acceleration period is 16.66 ms. The last 12% (2 ms) of the sinusoidal acceleration cycle produces only a 1.8% change in energy and a correspondingly small change in revolution frequency. These relatively static conditions provide an ideal environment for destructive resonances to grow in a machine operating near its stability limit. Since we use one turn extraction, it is relatively easy to extract "early" while the energy rate of change is still significant, some 2 ms before B_{max}. B_{max} is raised to a 475 MeV equivalent level to keep the extracted proton energy at 450 MeV.

Figure 4 shows two 2000 pulse histograms of variation in beam lost during a) acceleration cycle with extraction at 16.66 ms and b) acceleration cycle with extraction at 14.66 ms. In both cases, the extracted beam energy is 450 MeV. Each histogram is taken with a rigidly regulated injection of 2.33 x 10^{12} protons per pulse and no "scrambling" of the longitudinal phase space. The base lines in the figure represent the repeatable fixed loss (2.5 x 10^{11} per pulse) that occurs during injection, capture and early acceleration while the distribution of points represents the variable loss due to the instability being discussed. A scale size for 3 x 10^{11} loss per pulse is shown on the figure. Efforts were made to keep other operating conditions as identical as possible to make a meaningful comparison of the two operating modes.

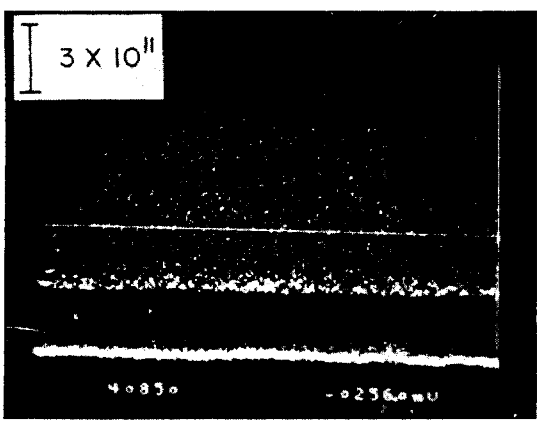

Fig. 4. Beam loss histograms -- 2000 pulses.
Upper pattern: extraction at B_{max}.
Lower pattern: extraction 2 ms before B_{max}.

In the preceding paragraphs we have implied that our instability is caused by high instantaneous current. The excess current seems to be caused by insufficient rf voltage. Increasing the peak magnetic field to 475 MeV from 450 MeV increases our need for rf voltage amplitude yet the beam is clearly more stable. Apparently reducing the allowable resonance growth time more than overcomes the effect produced by the slightly denser bunch which results from the increase in $\dot{B}_{max}$.

The beam extraction time in the IPNS accelerator varies by ±100 μs since extraction must be synchronized to the energy selection slot in a neutron chopper rotating at 20,000 rpm. Extraction even earlier when the energy rate of change is greater might further benefit the accelerator stability limit but the energy variation caused by the 200 μs uncertainty in extraction time required by the neutron choppers would then make extraction and transport lossy.

References

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