VERTICAL INSTABILITY AT IPNS RCS*

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Abstract

The Rapid Cycling Synchrotron (RCS) of the Intense Pulsed Neutron Source (IPNS) at ANL accelerates $> 3.0 \times 10^{12}$ protons from 50 MeV to 450 MeV with 30-Hz repetition frequency. During the acceleration cycle, the rf frequency varies from 2.21 MHz to 5.14 MHz. Presently, the beam current is limited by a vertical instability. By analyzing turn-by-turn beam position monitor (BPM) data, large-amplitude mode 0 and mode 1 vertical beam centroid oscillations were observed in the later part of the acceleration cycle. The oscillations start in the tail of the bunch, build up, and remain localized in the tail half of the bunch. This vertical instability was compared with a head-tail instability that was intentionally induced in the RCS by adjusting the trim sextupoles. It appears that our vertical instability is not a classical head-tail instability [1]. More data analysis and experiments were performed to characterize the instability.

INTRODUCTION

The RCS is a ring with six-fold symmetry and combined-function magnets. The two rf cavities (harmonic number 1) are located on opposite sides of the ring and accelerate the proton beam from 50 MeV to 450 MeV while the rf frequency varies from 2.21 MHz to 5.14 MHz in about 14 ms. A third rf cavity has recently been added to provide second-harmonic rf over the first 4 ms of the acceleration period [2]. Currently, the RCS runs with a current of ∼15 μA. At this current level, the vertical instability grows in the last 4 ms before extraction. The instability is suppressed by phase modulation (PM) of the rf voltage, varying the phase between the two fundamental-mode cavities by about 5 degrees at about twice the synchrotron frequency. This PM is applied for about 2 ms, beginning about 10 ms into the acceleration cycle.

OBSERVATION OF THE INSTABILITY

Observation of the Beam Loss

The major diagnostic methods we have available are the BPMs and the resistive wall monitor (RWM). In Fig. 1, the RWM measurement results are shown for cases with and without the instability. With the instability, particles are lost quickly starting ∼12 ms after injection. As is evident in Fig. 1, the particles get lost in the tail of the bunch and the bunch gets shortened. When we look at the spectrum during the instability, Fig. 2, we can see that the amplitude of the lower sideband is higher than that of the upper sideband. This indicates that a slow-wave instability is developing [3]. Since the revolution frequency varies from 2.21 MHz to 5.14 MHz, the sampling window in time for FFT is limited to be less than 50 μs to avoid a frequency shifting effect. In the figure, it should be noted that the instability gives a broadband spectrum; the sidebands are strongest near 55 MHz.

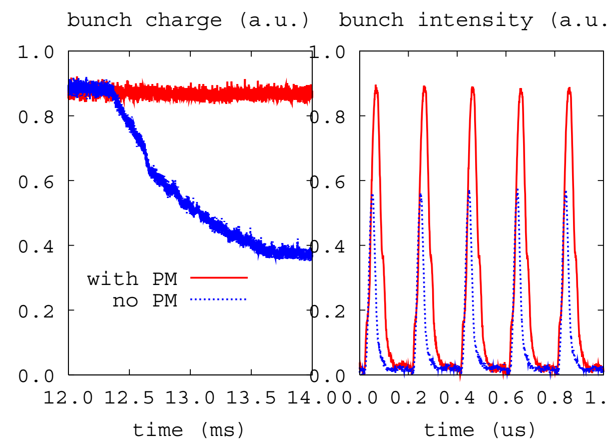

Figure 1: Beam loss observed with resistive wall monitor, phase modulation is used to suppress the instability.

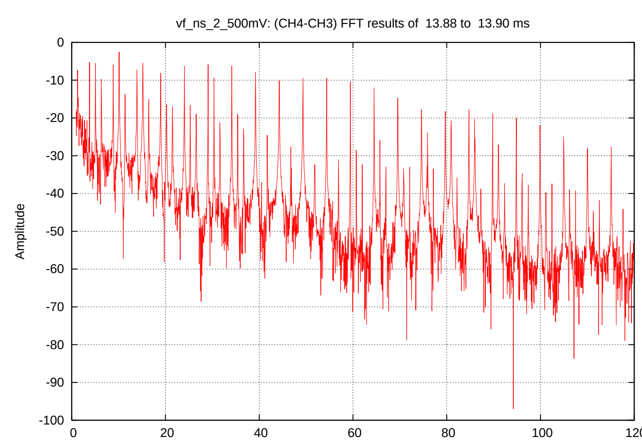

Figure 2: Spectrum during instability.

Measurements with BPM

Our BPM is a split-shoe-box type. The length of the BPM is 5 cm, while the proton bunch is more than 10 me-

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ters long. The signal from the BPM is therefore the time derivative of the bunch intensity. Both beam intensity and centroid position information can be extracted from the BPM signal. For dynamics analysis, we need to acquire the centroid motion on a turn-by-turn basis. There is a slow random shift of the baseline in the BPM signal; because of it, the simple integration of the BPM signal cannot be used for this centroid measurement. We therefore made some compensation to the integrated BPM signal:

- After integration, data for each turn was identified by checking the local minimum and maximum points of the integrated BPM signal.
- After turn boundaries were obtained, compensations were made to remove the contribution from the slowly varying baseline shifting during the integration process for each individual turn.

After compensation, we were still unable to see the centroid motion dynamics. This is because the measured data is naturally based on a fixed time basis. When the protons get accelerated, they move faster and faster, β increases from 0.3 to 0.7 for full cycle, and the revolution period gets shorter and shorter. However, since we have obtained turn-by-turn beam intensity after compensation, we can transfer data for each turn from a time basis to an rf phase basis. Then we can overlap data for many turns to see the centroid motion.

The Observed Instability

Figure 3 shows a typical result of analyzed BPM measurements during the instability, and where the chromaticity is nagtive. We overlapped BPM data for 50 consecutive turns. In the bottom graph, 50 turns data are enough to show the envelope of the oscillation of the centroid. The transverse size of the proton bunch is relatively large; when the centroid of the bunch oscillates at an amplitude of up to one fourth of the beam pipe radius, particles are easily lost.

We have never observed oscillations in the head of the bunch; it seems that the oscillation stops right at the peak of the intensity. We observed that the oscillation from its onset through the extraction of the bunch, which is a period of up to 3 ms, depends on the bunch charge. With less bunch charge, the instability starts later. The full evolution picture of the oscillation can be found in [4]. The synchrotron frequency at the time when the instability occurss is about 5 kHz; therefore our observations cover more than ten synchrotron periods. In no case we observe the oscillations entering the head region. We do observe the bunch length and peak intensity varying because of the synchrotron motion when the instability occurs. We also observe mode 1 oscillations when the bunch is longer, as shown in Fig. 4.

More information can be obtained by analyzing just one small slice (slice width, 5 degrees in rf phase) in the center of the oscillation in the tail and observing how it evolves with time. As can be seen in Fig. 5, soon after the oscillation starts, the beam starts to lose particles. The upper graph shows the BPM sum signal, and the bottom graph shows the BPM difference signal in the tail. Oscillation does not stop even when the bunch charge has dropped significantly. If we look at neighboring slices, we can note that the slice closer to the tail starts oscillations earlier and loses particles earlier. Even the whole slice can be lost, which shows that the bunch is shortened.

We further observe that the oscillations are damped at a frequency close to the synchrotron frequency. The reason for this damping could be the exchange of particles during the synchrotron motion.

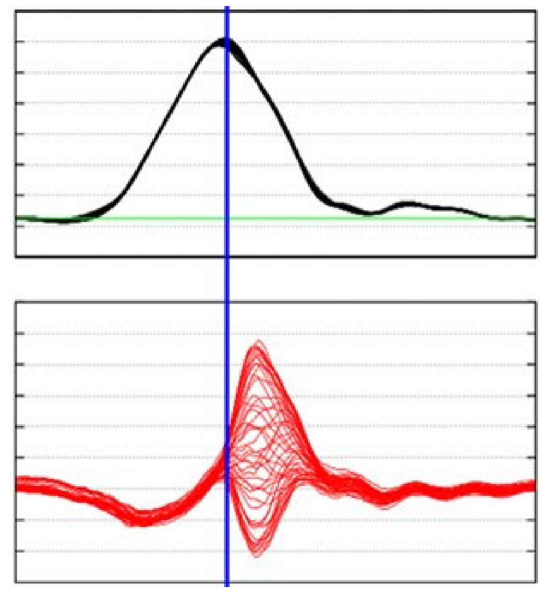

Figure 3: The centroid oscillations in the tail, mode 0. Upper graph: the sum of the top and bottom BPM signals; bottom graph: the difference of top and bottom BPM signals.

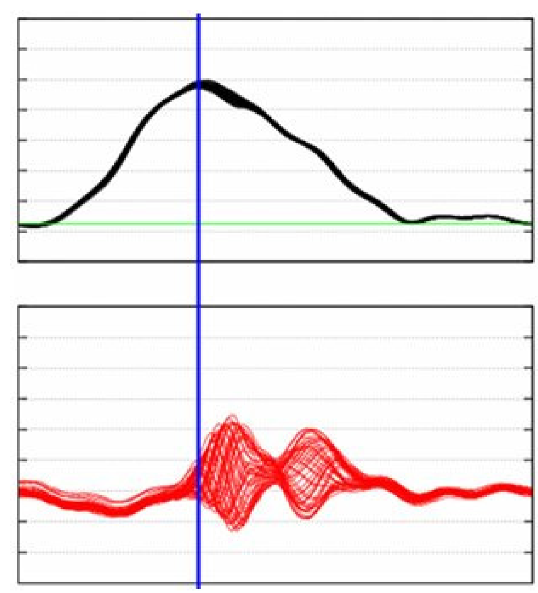

Figure 4: The centroid oscillations in the tail, mode 1.

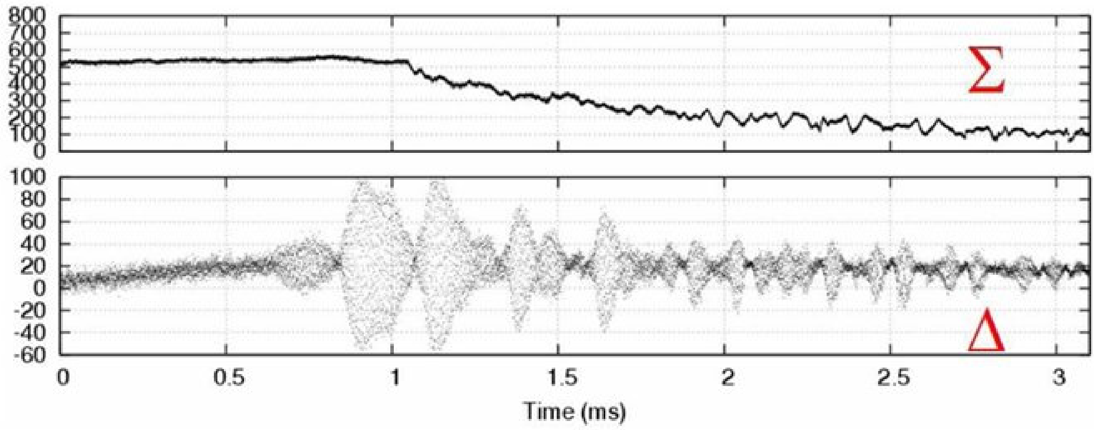

Figure 5: Comparison of the beam loss and tail slice oscillation for a 3.2 ms period before extraction. Upper graph: sum signal of the tail slice; bottom graph: difference signal of the tail slice, with arbitrary unit.

Comparison with Classical Head-Tail Oscillation

In the 80s, an observed head-tail instability limited the beam current in the RCS to be less than 5 μA. Sextupoles were added to make the chromaticity negative for the RCS, a machine operating below transition. This cured the head-tail instability.

In order to characterize the tail oscillation, we turned off the power supplies to the sextupoles. Using the same analysis as described above, we observed a classical head-tail instability, see Fig. 6. The oscillation in the classical head-tail instability covers the full bunch. This is quite different from the above-mentioned tail oscillation.

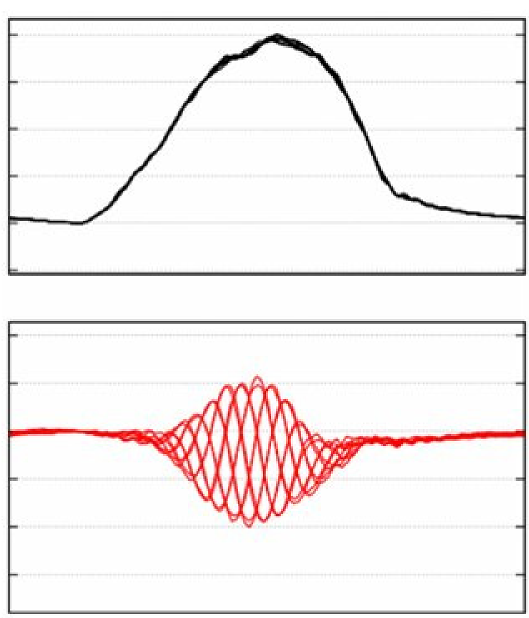

Figure 6: The centroid oscillations in head-tail instability induced in the RCS. Upper: the sum of BPM signals; bottom: the difference of the BPM signals.

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Currently, the vertical instability is suppressed by phase modulation of the rf voltage [5]. The phase modulation effectively increases the momentum spread allowing Landau damping to suppress the instability.

SUMMARY

We have presented an analysis of the vertical instability that limits the beam current in the RCS of IPNS. The centroid oscillation is confined in the tail half of the bunch, which is quite different from a classical head-tail instability. A possible cause of the observed vertical tail oscillation is an electron cloud effect. In the trailing edge of the proton bunch, electrons are able to escape from the proton beam potential well and initiate a secondary electron production avalanche [6]. We are currently investigating this possibility, but to date have not observed any direct evidence of such an avalanche. We are also investigating the effect of the machine impedance [7].

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