OBSERVATIONS OF UHF OSCILLATIONS IN THE IPNS RCS PROTON BUNCH

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Abstract

The Intense Pulsed Neutron Source (IPNS) Rapid Cycling Synchrotron (RCS) accelerates 3.2x10E[12] protons from 50 MeV to 450 MeV in a single bunch (h=1) at 30 Hz. The rf frequency varies from 2.21 MHz to 5.14 MHz during the 14.2 ms acceleration interval. To maintain stability of the bunch, phase modulation is introduced to the rf at approximately twice the synchrotron frequency (synchrotron tune is 0.0014). This phase modulation causes a parametric quadrupole oscillation to develop in the bunch, and as this occurs, the bunch spectrum shows a significant increase in high frequency content. Without phase modulation, the beam experiences an instability which results in the loss of a large fraction of the charge 2-4 ms prior to extraction. It is unclear if the stability imparted to the beam by phase modulation comes from the quadrupole oscillation or from the high frequency excitation. A longitudinal tracking code has been modified to include amplitude and phase modulation of the bunch. The numerical analysis is used to compare growth rates with those observed in the machine. The results of this analysis will be important as we introduce second harmonic rf with a new third cavity in the RCS later in 2005.

INTRODUCTION

Acceleration of charge in the IPNS RCS leads to an instability when the injected charge exceeds approximately 2×10^{12} protons (0.3 μC). Phase Modulation (PM) of the rf voltage[1,2,3,4] driving the two ferrite-loaded acceleration cavities generates a quadrupole oscillation in the h=1 bunch. The oscillation, driven at approximately twice the synchrotron frequency, leads to an increase the rms momentum spread of the bunch. PM starts at about 9.5 ms into the acceleration cycle as indicated in Figure 1. The 70-μs injection pulse is initiated between 180 and 280 μs before t=0, the time of minimum B-field (B_{min}). Bunch momentum follows the magnetic field, while the rf frequency follows β. PM stabilizes beam losses allowing the bunch to survive more or less intact up to 450 MeV, the extraction energy. Extraction occurs before B_{max}, about 14.2 ms after injection. Utilizing PM, the RCS presently accelerates 3.2×10^{12} protons per bunch with an overall transmission efficiency of 87-88 % ($3.6\text{-}3.7 \times 10^{12}$ protons injected).

RF BEAM DATA

The period of PM lasts approximately 2 ms. During PM, oscillations in the beam expand significantly in frequency space as shown in Figure 2. A previous paper

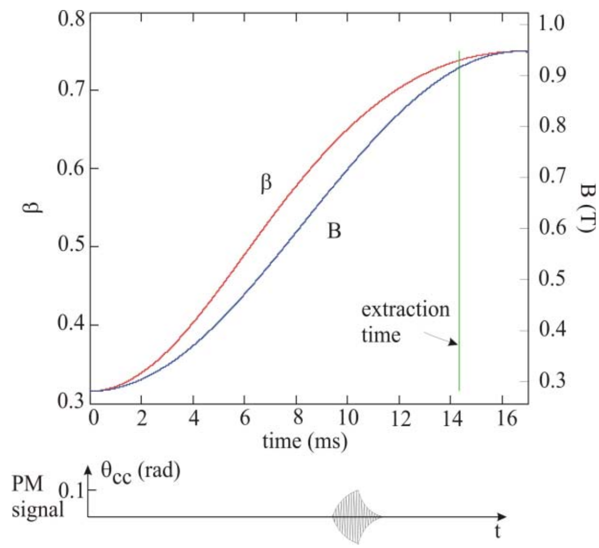

Figure 1: β, B, and PM in the IPNS RCS

[5] presented data which indicated the appearance of broadband frequency features after the initiation of PM. That data was obtained from split-can ("Pie") electrodes located in the RCS. However, the conclusion regarding the presence of the broadband spectral features was

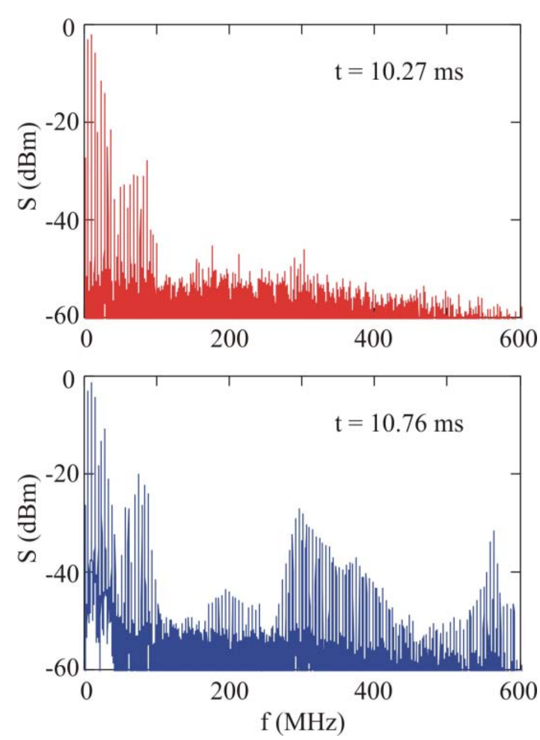

Figure 2: The appearance of UHF in the RCS with PM

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incorrect. Initially, the data from these position electrodes were sampled using a fast oscilloscope at a rate of 250 MS/s. The features were again observed when the sampling rate was increased to 500 MS/s; however, the spectral features disappeared when the data sampling rate was subsequently increased to 1.25 GS/s. A comparison of pie electrode spectra, recorded at the same time in the cycle, is presented in Figure 3 for sampling rates of 250 MS/s and 1.25 GS/s. This behavior implies that high frequency beam components in the range of 250 MHz-600 MHz were aliased to lower frequencies at the slower sampling rate. The missing spectral features in Fig.3 do not vanish with the higher sampling rate; the signals are still present at higher frequencies. The time signal from the pie electrode is proportional to dI/dt (or dI/dz); therefore, it is also proportional to the longitudinal space-charge electric field in the bunch.

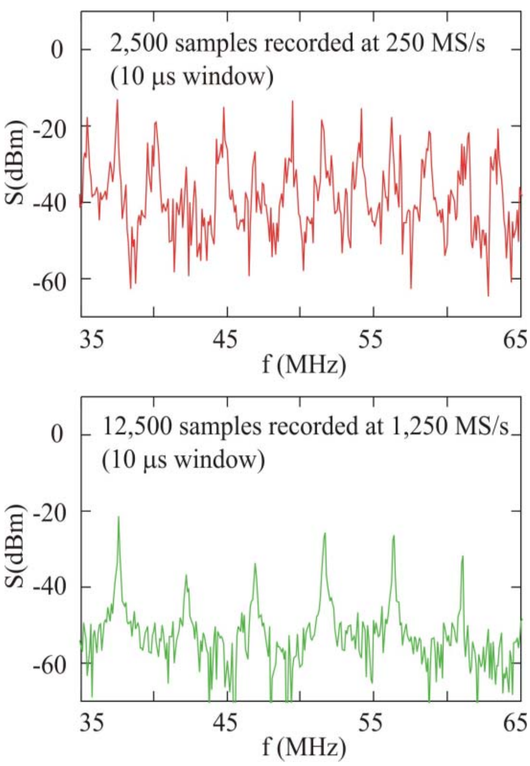

Figure 3: Aliased (top) and clean (bottom) spectra

The generation of UHF frequency components occurs shortly after the appearance of a longitudinal quadrupole oscillation in the beam, which in turn begins a few hundred microseconds after PM is applied. The way PM is applied also causes amplitude modulation [6] of the gap voltage. The rf voltage levels vary by ±5 percent.

Pie electrode data without PM, strongly suggests that a vertical instability near the end of the acceleration cycle leads to a destructive high-energy loss in the beam. Spectra from approximately the same time in the cycle with and without PM are compared in Figure 4. In the case without modulation, large, narrowband (coherent) features appear near the vertical tune frequencies. At higher harmonics, the sideband amplitude exceeds that of

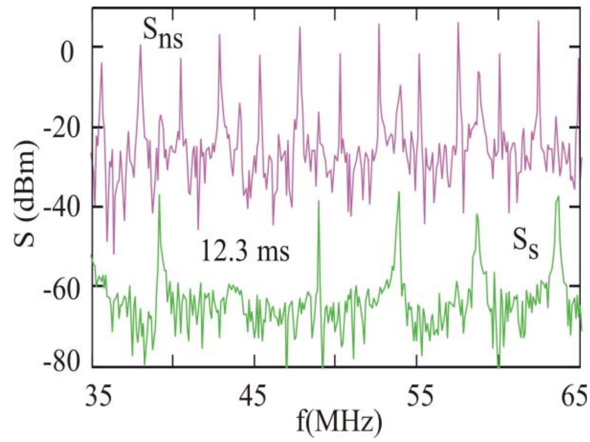

Figure 4: Pie electrode spectra with (S_s) and without (S_{ns}) PM, where S_s=S-10 dB and S_{ns}=S+40 dB, at t=12.3 ms.

the primary harmonic. Also, though both lower and upper sidebands appear, generally one side dominates, indicating dipole motion. As shown in Fig.4, with PM, sideband structure is not observed in the band from 35 to 65 MHz.

ANALYSIS

Two questions arise regarding the behavior of the beam as described by the preceding data: 1) does the stability of the beam come directly from the PM through the quadrupole motion of the bunch, and 2) what is the source of the high frequency spectrum of the beam? Regarding the first question, the longitudinal analysis code CAPTURE_SPC [7,8,9] has been modified to include the effects of PM on the beam. Using CAPTURE_SPC, generation of the quadrupole motion can be simulated and an increase in the momentum or energy spread of the beam can be seen with the application of PM. The quadrupole oscillation mechanism increases ΔE during the same portion of the synchrotron cycle that the instantaneous current is rising. The coasting beam stability threshold against microwave instability is given as[10],

$$\frac{|Z_e|}{n} \le F \frac{E|\eta|}{e\beta^2} \frac{\left(\Delta E(\phi)/E\right)^2}{I(\phi)} \qquad (1)$$

where Z_e is the coupling impedance to the wall, n is the harmonic index, F is a form factor for the bunch, η is the slip factor, e the charge, ϕ the phase, and I the instantaneous current. Assuming an initial energy spread of ΔE_o, and an oscillating energy spread of amplitude ΔE_a, where the oscillation is approximately sinusoidal with frequency $2\omega_s$, then the energy spread as a function of time can be expressed as,

$$\Delta E(t) = \Delta E_o + \Delta E_a \sin(2\omega_s t) \qquad (2)$$

where ω_s is the synchronous frequency. It is assumed that the elevated stability threshold is due primarily to an increase in the rms energy spread,

$$\Delta E_{rms} = \sqrt{\frac{1}{T}\int_0^T \Delta E^2(t)dt} = \sqrt{\Delta E_o^2 + \Delta E_a^2 / 2} \tag{3}$$

In the case where $\Delta E_a = \Delta E_o$, $\Delta E_{rms} = (3/2)^{1/2} \Delta E_o = 1.225 \Delta E_o$; in other words, the rms energy spread is increased by 22.5 percent. Using Eq. 1, the expected increase in the threshold current limit is approximately twice this increment or 45 percent. Assuming an average threshold current limit of 10-11 μA, the predicted upper limit with the PM is then 14.5-15.9 μA; very much in line with the typical range of average operating current in the RCS. Therefore, it would appear that the answer to the first question above is yes, PM can provide enough additional energy spread through generation of a quadrupole oscillation to stabilize the beam up to the current limits presently observed. A comparison of the bunch phase-space distribution before and after the introduction of PM, predicted by CAPTURE_SPC, is presented in Figure 5.

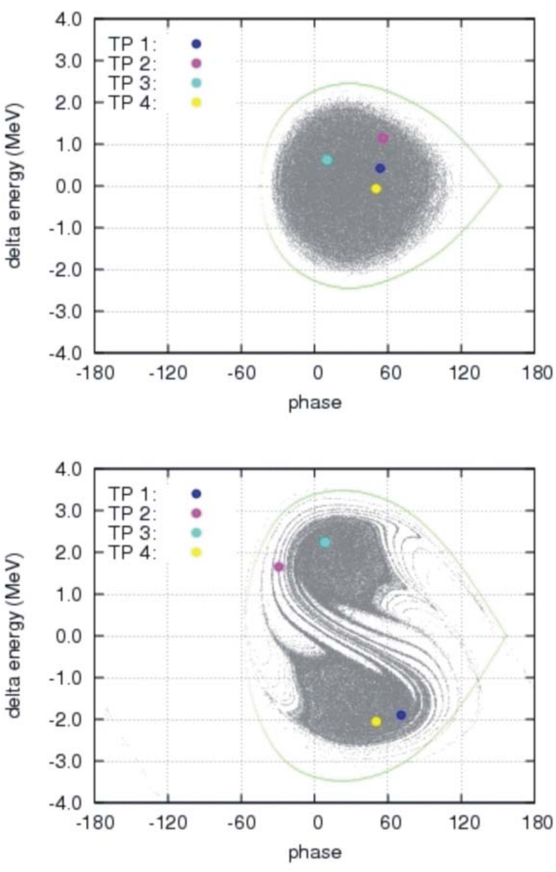

Figure 3:CAPTURE_SPC phase-space plot before and after the introduction of PM, the PM amplitude is 4.3°.

The lower plot (after PM) is chosen to show the peak amplitude of oscillating energy spread. CAPTURE_SPC clearly shows the generation of a quadrupole oscillation in the bunch with PM

Regarding the second question posed above on the source of the high-frequency motion observed in the bunch, the CAPTURE_SPC simulation does suggest that with PM, a fine structure in the bunch may appear. In addition, the ionization of the background gas within the RCS chamber and the generation of a beam-driven plasma may also have a role in the generation of the spectrum. Further work on this latter topic will be addressed in a later paper.

FURTHER WORK

Going forward, it is important to determine if PM will be required with the introduction of second harmonic (SH) rf in the RCS, scheduled to begin later in 2005. Initially, SH rf will be introduce only during the early portion the acceleration cycle (first 4-5 ms). In this case, the answer would clearly be yes since SH early may allow more charge to be injected, but only fundamental rf will be available for the entire acceleration cycle. When SH rf is available for the entire cycle, the need for PM may still be present since it is possible that the SH rf may lead to a bunch with a reduced energy spread. On the other hand, SH rf will allow the bunching factor to be increased reducing the instantaneous current. Also, it will be important to determine the best frequency to operate the PM. In this regard, it is expected that CAPTURE_SPC will be helpful.

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