Reducing the Coupled-Bunch Oscillation in the Fermilab Booster by Optimizing RF Voltage

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Abstract

In the Fermilab Booster, the coupled bunch oscillation is excited between transition and extraction by parasitic high order modes (HOM) in 17 RF cavities. The growth rate is determined by the coherent frequency shift and natural Landau damping due to nonlinearity of RF waveform. The passive damping and active feedback are normally used to reduce coherent frequency shift. Here we report that Landau damping can be enhanced through careful programming of RF voltage through the acceleration cycle. It is very effective during ramping where synchronous phase is big and bucket area is very sensitive to the RF voltage. In the case of a stationary bucket, the landau damping is not sensitive to RF volatge.

1 Introduction

The Fermilab Booster is a fast cycling synchrotron, accelerating protons from 200 Mev to 8 Gev in 33 ms. The 8 Gev beam extracted from the Booster will be injected into the Main Ring (MR), which has a very limited transverse aperture. To achieve high transmission in the MR, it is desireable that the Booster beam has small momentum spread. Also the beam accelerated in the MR will either be used to produce antiprotons, or coalesced to single bunch. Both the antiproton stacking and the proton coalescing prefer beam from the Booster with small longitinal emittance.

In the Booster the longitudinal emittance growth is due to transition crossing and longitudinal coupled bunch instability after transition. Some years ago the γ_t jump system [1] was implemented to increase effective transition crossing speed, thus reducing the longitudinal emittance blow up through transition. Although the γ_t jump did reduce emittance growth due to transition crossing, the smaller bunch after transition resulted in more pronounced longitudinal coupled bunch instability. So the γ_t jump system was not used operationally. So it is coupled bunch oscillation that limits the longitunal performance in the Booster.

The individual coupled bunch oscillation mode has been identified to be stronghly correlated to the parasitic modes in the RF cavities [2]. There are mainly two clusters of coupled bunch mode, one around mode 16 and another around mode 36. Following the installation of resistive dampers [3] [4] in the the RF cavities, modes around mode 16 are successfully damped. Modes 34, 35 and 36 still persist. The narrow band active damper is able to damp any one of three modes, but not all of them simutanously. The wide band system is under design [5]. The coupled bunch oscillation is still the limitation of longitudinal performance. Operationly the couple bunch oscillation is reduced by mistuning transition timing. If we try to operate at nomial(optimized) γ_t jump timing and phase jump timing, very strong CBM is excited.

We report the couple bunch oscillation can be reduced by careful programming of RF voltage after transition. The nomail RF voltage curve has bucket area larger than 0.2 ev-s, which is much larger than the beam emittance (about 0.06 ev-s). So one way to increase the synchrotron tune spread is to let beam fill the bucket by the reduction of RF voltage [6].

2 Review of Sacherer Theory

The rule of thumb for coupled bunch instability is [7]

$$\frac{S}{\Delta\omega_m} > \frac{4}{\sqrt{m}} \quad (1)$$

where S is the synchrotron tune spread inside the bunch, and $\Delta\omega_m$ is the coherent frequency shift of mode m caused by a resonator shunt impedance R_s and quality factor Q

$$\Delta\omega_m = \frac{\omega_s R_s I D F_m(\Delta\phi)}{2\pi V_{rf} B} \quad (2)$$

where I is beam current, ω_s synchrotron frequency at the center, $F_m(\phi)$ is the form factor which specifies how efficiently the resonator can drive a certain mode m. The term D depends on the attenuation of the resonator signal between two bunches, and is about 1 for high Q resonator.

The quantity we want to maximize is

$$\frac{S}{\Delta\omega_m} \propto \frac{S}{w_s} V_{rf} B \frac{1}{N R_s} \quad (3)$$

The role of mode damping and the active feedback is to reduce the effective shunt impedance. The RF voltage should to be programmed to maximize the figure of merit

$$FOM = \frac{S}{w_s} V_{rf} B \quad (4)$$

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assuming the form factor is a constant. When ϕ_s is big, we reduce RF voltage by little to end up increasing the fractional synchrotron tune spread dramatically. But for a stationary bucket, the bunch length changes as $V_{rf}^{-\frac{1}{4}}$. To the first order approximation, $\frac{S}{w_s}$ is proportional to the square of bunch length. So

$$FOM \propto V_{rf}^{\frac{1}{4}}, \tag{5}$$

which has a very weak dependence on V_{rf}.

3 Result in the FNAL Booster

By reducing the RF voltage after transition as shown in Fig. 1, the coupled bunch oscillation is successfully reduced. Comparing the spectrum in Fig. 2(trigged at 34ms, 1.5ms before extraction), coupled bunch mode has been lowered by 8 Db on the average of 32 pusles. Upon inspection, all three primary modes (34, 35 and 36) have been damped. With this new RF curve, there is couple bunch oscillation till roughly 32ms in the cycle. After that the synchrotron tune spread is not big enough to suppress coupled bunch instability entirely. The mountain range plot is shown at extraction with old RF curve at Fig. 3 and with the new one at Fig. 4.

As a result, the longitudinal emittance is further reduced and the transmission efficiency is increased. A new MR intensity record is created 2.17×10^{12} for 6 Booster turns (2.5×10^{12}), which is helpful to improve the antiproton stacking rate. For 7 Booster turns, the booster can accelerate 2.6×10^{12}, of which (2.53×10^{12}) injected to MR and 2.20×10^{12} accelerated to 120 Gev.

4 Discussion

The result in the booster verifies that the RF voltage reduction is a very effective way to increase landua damping when ϕ_s is bigger and becomes ineffective when synchrotron phase is small at extraction.

The reason for big variation of coupled bunch oscillation amplitude from pulse to pulse is not well understood. Good understanding of this variation may provide us better way to of controlling.

With upcoming 400 Mev upgrade, the intensity in the Booster will be doubled. So the coherent frequency shift will also be doubled if the longitudinal emittance is the same as now. Hopefully the wideband actice feedback will come to the action. But the feedback system is only sensitive to the coherent dipole oscillation. Once dipole oscillation comes under control, the potential higher order (likely quadrupole) oscillation will become a concern.

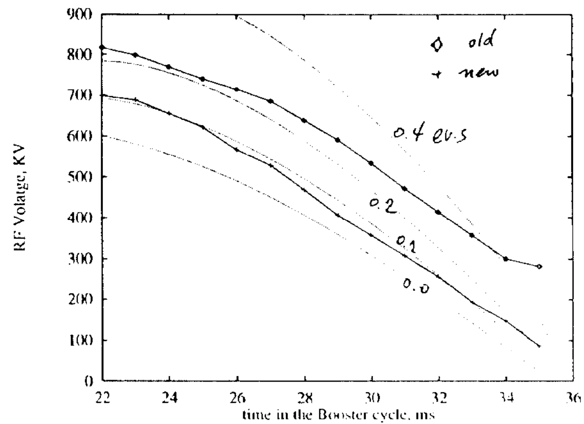

Figure 1: The RF voltage curve after transition in the Booster. The old curve starts with a bucket area 0.2 evs and increases to larger than .4 evs at extraction. The new starts with .1 evs and increases to 0.2 evs.

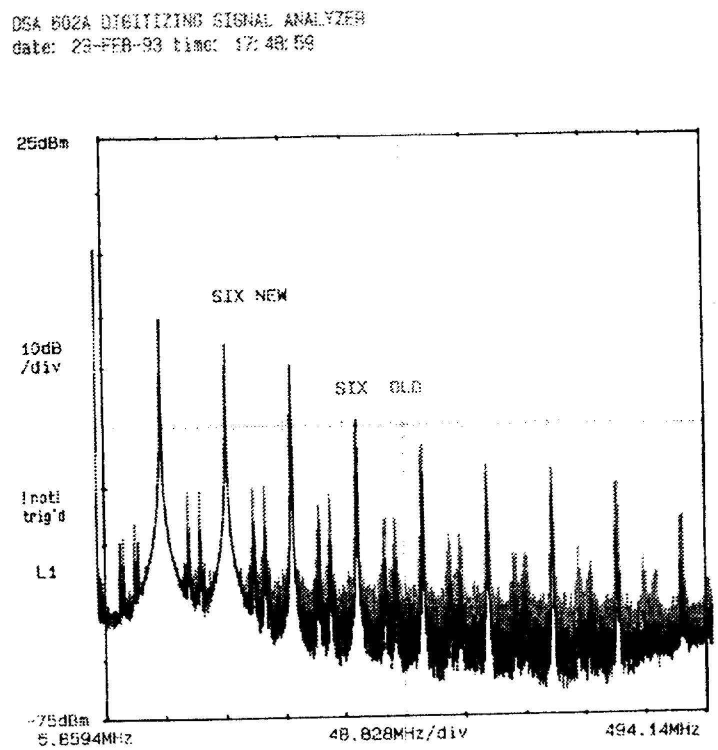

Figure 2: The beam spectrum in the Booster at 34.5ms averaged with 32 pusles. The reduction of 8 Db in coupled bunch modes with new RF rf curve is visible.

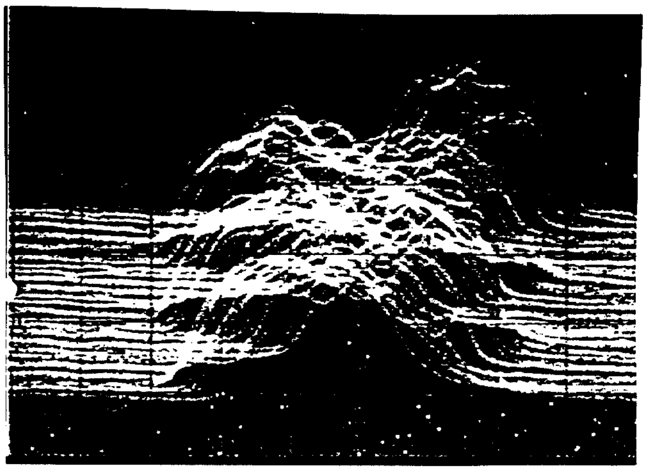

Figure 3: The typical moutain range display at extraction (33.5–35.5 ms) with old RF curve. The intensity is 2.2×10^{12}, the swip is 1 us/div. The γ_t jump trigs at 18.72 and the transition phase jumps at 18.76ms.

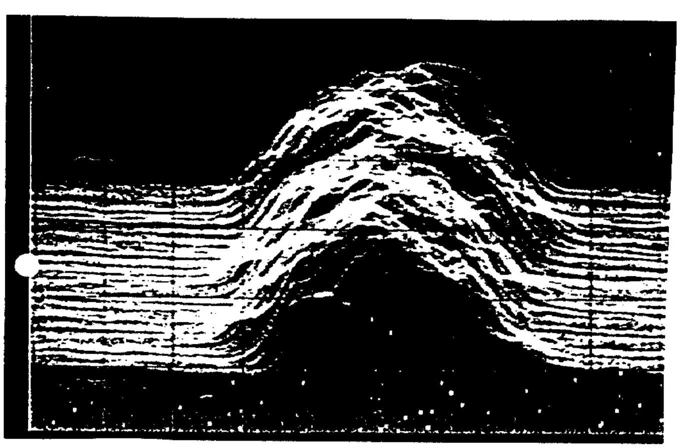

Figure 4: The same mountain range plot with new RF curve.

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