OBSERVATION AND CURE OF LONGITUDINAL COUPLED-BUNCH INSTABILITIES IN THE FERMILAB MAIN RING

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Abstract

One goal of the Fermilab Main Ring accelerator during the Fixed target run is to keep the longitudinal beam oscillations as small as possible. It is found that when the proton beam intensity reaches a certain value, longitudinal beam oscillations rapidly grow. This motion can be explained by the longitudinal beam instability model. Installed active feedback system has successfully eliminated the instabilities and record intensities are achieved. We discuss the observations that indicate the damper systems are necessary. The results of the instability growth measurements are compared with a simple model.

1 INTRODUCTION

Longitudinal bunched beam modes and their electromagnetic interaction with the beam were first described by Sacherer [1]. For M equidistant bunches, there are M coupled bunch modes characterized by n-waves $0 \leq n \leq M-1$ around the storage ring. The theory of longitudinal bunched beam contain radial as well as within-bunch modes. Normally only the lowest radial and azimuthal modes are observed. This could be due to the fact that higher order modes are Landau damped. As mentioned, the interaction between charged particles and their environment, such as RF cavities, kickers and bellows can drive the beam unstable resulting in unwanted longitudinal coherent beam oscillations. These oscillations will cause the eventual growth in longitudinal emittance. Longitudinally, the beam is accelerated by two fields: One is externally powered in RF cavities, the other comes from the wake fields which are proportional to the beam intensities. For low intensities, the wake potential is small enough that its effect can be neglected. As the beam intensity increases, the wake potential produced by the frontal bunches in the RF cavities need to be considered in the particle equation of motion. In the Main Ring, the wake potential for the higher order cavity modes can reach several kV for a beam with 2E12 particles per bunch while the peak fundamental RF voltage is about 4MV per turn. By making comparisons, it is concluded that the observed beam behavior can be fully explained by a relatively simple simulation model. An active feedback system has reduced the 225 MHz signal associated with the longitudinal instabilities.

2 EXPERIMENTAL RESULTS

Data are collected by observing signals from a resistive wall monitor with a Tektronix 2 GHz digitizer. The digitizer is triggered every 32 turns to capture ~10 synchrotron period worth of longitudinal profiles of the bunches (Fig.1). The resulting time series is then broken up into 1000 realizations. Each realization contains the turn by turn data for each bunch which are then individually Fourier transformed. The phase shift $\Delta\varphi$ of the perturbing bunch motion with respect to a reference bunch is $2\pi n/M$. We can then infer the wake field structure by calculating the wavenumbers $k_n=\Delta\varphi_n/\Delta x$ (Fig.2).

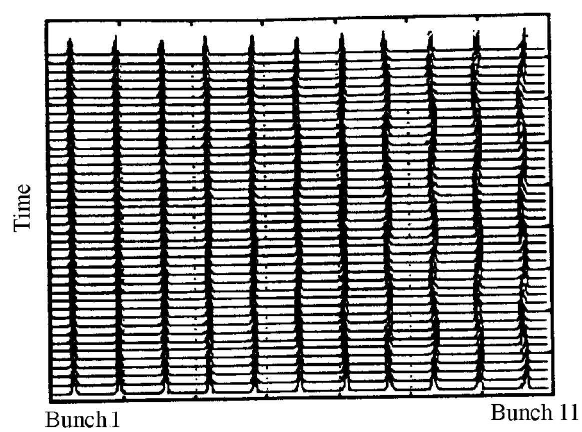

Fig.1) Waterfall plot of the first 11 bunches.

Another comparison can be made through the bunch length growth of both simulation and experiments with and

† Operated by the URA Inc.,under contract with the U.S. Department of Energy.

without the dampers. With the assumption of a Gaussian distribution, the density function $f(\tau)=f_o \exp(-\tau^2/2\sigma_\tau^2)$ can be Fourier transformed. σ_τ is the width parameter of a standard Gaussian distribution. From the first and third harmonic line of the spectrum, one can obtain the bunch length. $\sigma_\tau = 1/(2\omega_{53})(f(\omega_{53})/f(\omega_{159}))$.Fig. 3 shows the growth of the bunch length as the instabilities develops.

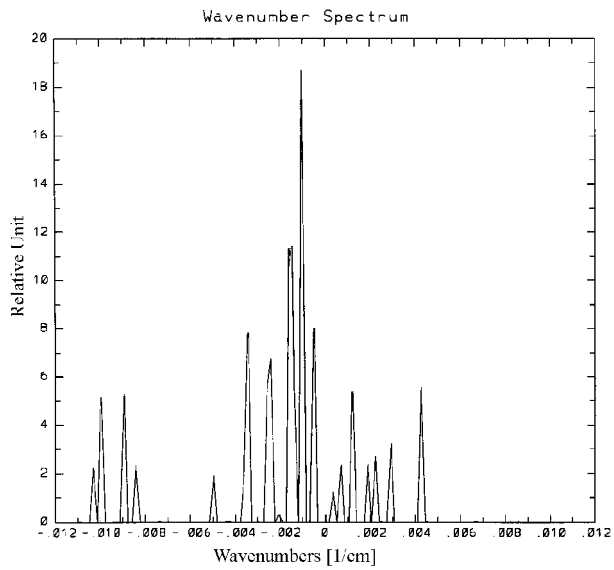

Fig.2) Measured two peaks associated with dipole and quadrupole oscillations between bunches 11 and 1 is shown.

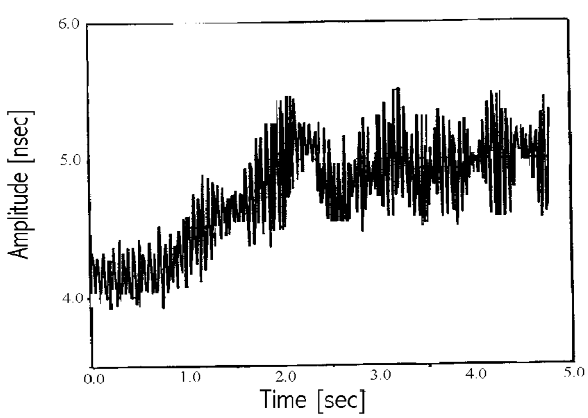

Fig.3) 150 Gev bunch length increases as the longitudinal coupled bunch instabilities occurs.

To understand the extend of short range wake fields, the beam is given an initial kick by a programmable digital phase shifter which shifts the phase of all 18 RF cavities by 20 degrees for 200 µsec (10 turns). The centroid position of each bunch can be found and compared with the unkicked case. The decay time τo for the oscillation is much longer than the bucket width (T_{RF}). The decay time for the higher order cavity modes can then be calculated. For example, the τ_{250} Mhz cavity mode is found to be ~.5µsec which is less than 21µsec revolution period but much larger than a bucket width .

3 SIMULATIONS

A simulation program similar to a simple resonator is written in MathWorks Simulink. Wake fields are accumulated continuously from bunch to bunch. Here 5 batches of 84 bunches are considered to be consistent with the experimental measurements. A Gaussian beam intensity distribution is assumed in the simulation. The bunch length for each bunch of 2e10 particles are calculated each turn. The bunch length of the 11^{th} macro particle is shown in Fig. 4. As measured experimentally in (Fig.2) the wake potential is not proportional to bunch number. This is due to the fact that the higher order mode frequencies are not an integer number of RF. The vector addition of the induced electric field can be positive or negative, which leads to increase or a decrease in the oscillation of the centroid of the bunches (Fig.5,6).

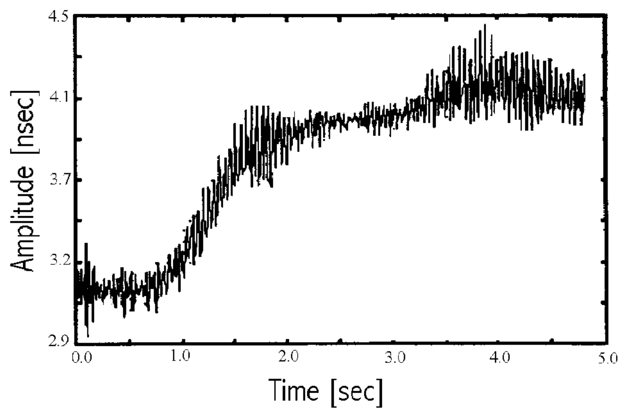

Fig. 4) Simulation of bunch length blowup vs Time.

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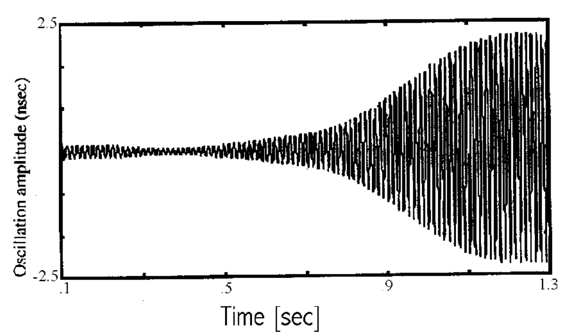

Fig.5) Simulation of 11^{th} bunch centroid from bucket center. For the RF frequency of 53 MHz, 1 ns is equal to 19 degrees of phase.

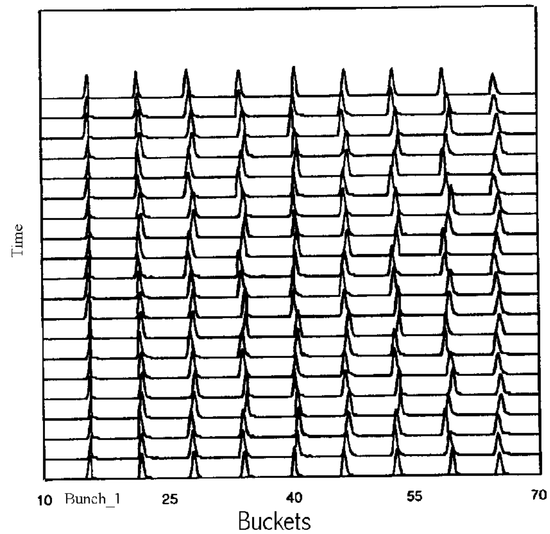

Fig.6) Waterfall plot of the simulated data after 1.3 sec shows the trailing bunches are affected by the cumulative frontal wake fields.

4 ACTIVE FEEDBACK

The *filter method* is used for longitudinal coupled bunch damping in the Main Ring. The longitudinal pickup and kicker together with specially shaped narrow band bandpass filter centered around revolution harmonic is used. The filter contain a notch centered exactly around the revolution harmonic. This notch serves the dual purpose of suppressing the unequal bunch line and providing a 180 degrees phase shift such that both upper and the lower sidebands are damped. Figures 7-9 shows

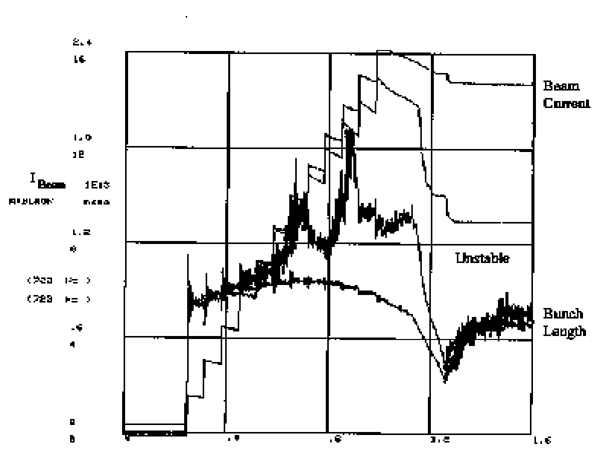

Fig.7) Current and bunch length of both stable and unstable beams are shown.

the effectiveness of the damping system.

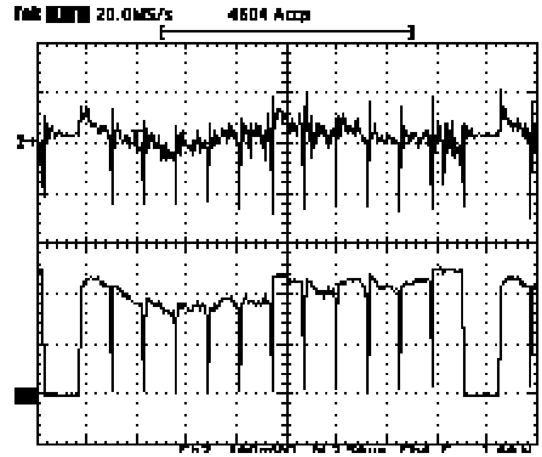
Fig.8) Dampers off: Phase (top) and amplitude (bottom) of beam intensity for 12 batches are nonuniform due to the instabilities.

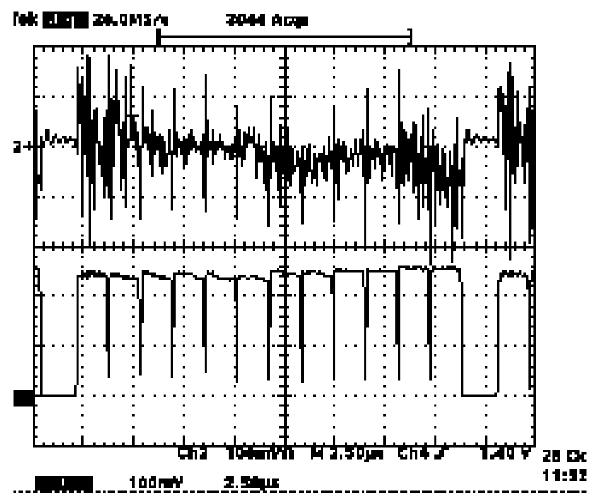
Fig.9) Dampers on: Phase (top) and amplitude (bottom) of beam intensities for the 12 batches are shown to be uniform.

5 CONCLUSION

A higher order mode impedance in the RF is verified to be the source and drive the beam unstable longitudinally. Simulation results agree with the measurements of the coupled-bunch instabilities. Oscillations are reduced by an active feedback system.

REFERENCE

[1] F.J. Sacherer, IEEE Trans. Nuclear Sci.,NS-28 (1973).