THE TEVATRON BUNCH BY BUNCH LONGITUDINAL DAMPERS

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Abstract

We describe in this paper the Tevatron bunch by bunch dampers. The goal of the dampers is to stop the spontaneous longitudinal beam size blowup of the protons during a store. We will go through the theory and also show the measured results during the commissioning of this system. The system is currently operational and have stopped the beam blowups during a store.

INTRODUCTION

As Run II begins its first year, unforeseen problems have started appearing which need to be fixed before higher luminosities can be achieved. One of the problems which started to appear at the beginning of 2002 is the rapid blowup of the longitudinal beam size during a store. See Figure 1. Although these blowups do not appear in every store, they seem to be weakly correlated with beam current. There are conjectures by the authors that the blowups are due to coupled bunch mode instabilities which arise from coupling to the higher order parasitic modes of the RF cavities. As these higher modes move as a function of temperature, the coupled bunch modes can be stable or unstable depending on where and how the higher order parasitic modes line up.

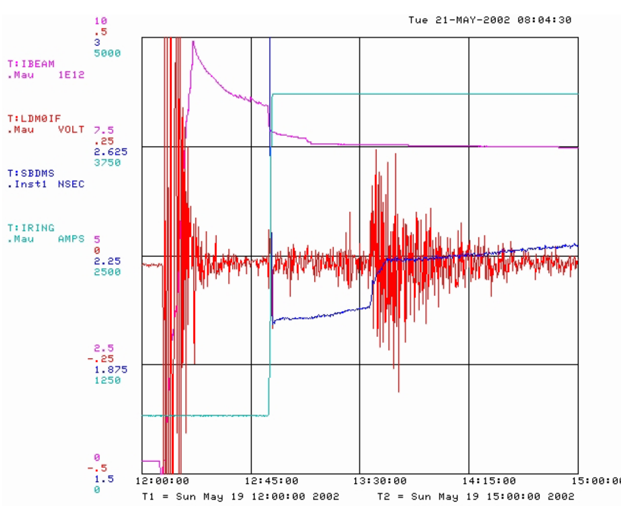

Figure 1: The beam blows up longitudinally (T:SBDMS) at about 1340hrs during the store which started at about 1300hrs. We see that when it blows up the phase signal of the bunch oscillates w.r.t. RF (T:LDM0IF). Plotted also are beam current T:IBEAM and the bus current T:IRING.

After much discussion, it was decided that the best course of action is to build a bunch by bunch longitudinal damper system. At first glance, the idea of using the RF cavity themselves as the source of longitudinal kicks on the beam seems to be difficult. This is because each of the four proton RF cavities has a high Q ($\sim 10^4$) near its resonance and thus its impedance falls off rapidly away from it. Therefore, the amplitude and phase response is not flat at all synchrotron sideband pairs and thus the dampers are not bunch by bunch. The solution to this problem is to build an equalizer that lifts up the impedance so that it looks constant away from the resonance. Besides the equalizer, the damper also needs a notch filter which suppresses the revolution harmonics (otherwise these harmonics will limit the gain of the loop) and differentiates in time the synchrotron sidebands. Lastly, we also have to time in the system so that the error signal of bunch n is applied exactly one turn later to kick bunch n.

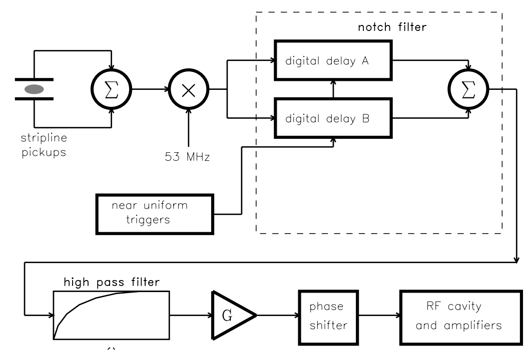

Figure 2: This figure shows the block diagram of the setup used for the longitudinal dampers.

SETUP

Figure 2 is a block diagram of the setup. The damper system starts at the stripline pickups which sum the beam signals at the two plates to produce a signal which is proportional to the longitudinal position of the beam. This signal is then mixed down with the Tevatron RF to produce a phase error (or quadrature) signal w.r.t. it. The error signal is then processed with electronics which perform the following:

- Equalize the impedance of the RF cavity.
- Suppress the revolution harmonics and differentiate the synchrotron sidebands around the revolution lines.

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- One turn delay so that when the dampers pick up the signal of bunch 1 it will kick bunch 1 one turn later.

Equalizer

The idea of using a hpf to equalize the impedance of the RF cavity comes from observing that if we model the RF cavity impedance $Z_{\rm RF}$ using an RLC circuit and define R_s as its shunt impedance, L as its inductance and C as its capacitance, then

$$Z_{\rm RF} = \frac{R_s}{1 - iQ\left(\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R}\right)} \tag{1}$$

If $\omega_R = 1/\sqrt{LC}$ is its resonant frequency and $Q = R_s\sqrt{C/L}$ is its quality factor, then the magnitude $\left|Z_{\rm RF}\right|$ is

$$\left|Z_{\rm RF}\right| = \frac{R_s}{Q\left|\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R}\right|} \qquad \text{when } Q \to \infty \tag{2}$$

which means that $\left|Z_{\rm RF}\right|$ has a $1/\delta\omega$ type dependence when $Q \to \infty$ and $\delta\omega/\omega_R \ll 1$.

Next, let us examine the response of a hpf. We introduce first a new variable $\Delta\omega = (\omega - \omega_{\rm RF})$ where $\omega_{\rm RF}$ is the RF drive frequency and $\omega_{\rm RF} \approx \omega_R$. For a hpf with a 3dB response at $\Delta\omega_{\rm 3dB}$, its response function $R_{\rm hpf}$ is

$$R_{\rm hpf}(\Delta\omega) = \frac{1 + i\frac{\Delta\omega_{\rm 3dB}}{\Delta\omega}}{1 + \frac{\Delta\omega^2_{\rm 3dB}}{\Delta\omega^2}} \tag{3}$$

and thus $\left|R_{\rm hpf}\right|$ has a $\Delta\omega$ dependence. At base band, the mixed down impedance of the RF cavity will have a $\left|Z_{\rm RF}(\Delta\omega)\right| \sim \Delta\omega$ dependance from (2) and when multiplied with $R_{\rm hpf}(\Delta\omega)$ will have a constant impedance in the region around $\omega_R \approx \omega_{\rm RF}$ and $\left|\omega_{\rm RF} - \omega\right| \ll \omega_{\rm 3dB}$.

Notch Filter

The notch filter used in the electronics serves a two fold purpose. First, it suppresses the revolution harmonics. Second, it differentiates the synchrotron sidebands around the revolution harmonics which tells the damper which direction to kick. In our setup, th notch filter is created with two digital delay lines. Its response is given by

$$R_{\rm notch}(\omega) = 1 - e^{-i\omega NT} \tag{4}$$

where T is the revolution period and N is the number of revolution periods in the delay. The choice of N is a compromise between the Tevatron's injection energy at 150 GeV and its top energy at 980 GeV and the phase and amplitude responses at these two energies. We chose $NT = 1/6f_s$ where $f_s \approx 88$ Hz is the synchrotron frequency at 150 GeV. Therefore, $N = 90$ when $T = 21$ μs. (Note: we have actually set $N = 91$ in the actual setup).

Triggers

In order for the digital delays to work they have to be triggered. The triggers which we use are uniform in time and spaced 7 buckets apart. These triggers also appear in the abort gap where there is no beam. The reason for having this pattern of triggers rather than having triggers where the bunches are is to allow us to use reasonable cable delays to ensure that the correct bunches are kicked. In the worst case scenario using equally spaced triggers, the cable length will be $7\,\text{buckets}/2 \approx 66$ ns for correctly hitting the right bunch. While for triggers where there are bunches only, the worst case scenario will be $140\,\text{buckets}/2 \approx 1.3$ μs of cable!

RESULTS

Finally, we get to look at the open loop response of the dampers. The first set of measurements are performed with delay B disconnected. See Figure 2. This is to get the delay to be exactly 1 turn, i.e. $\Delta t = 2\pi/\omega_0$. When the delay is made exactly right, we get nice anti-symmetric imaginary responses for all the modes. Three of the modes are shown as examples in Figure 3.

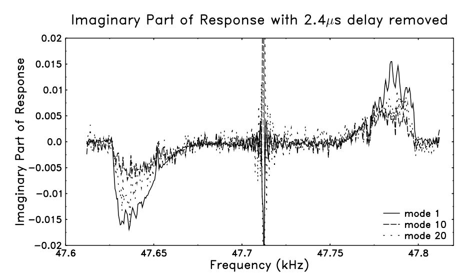

Figure 3: This graph shows the imaginary part of the response of modes 1, 10 and 20 after the delay is corrected. We have superimposed all the three graphs on top of each other by shifting the frequency of mode 10 by $-10f_0$ and mode 20 by $-20f_0$.

With the delay set in Delay A, we can now make the notches by reconnecting back Delay B and by setting the delay in this card by $N(= 91)$ revolution periods w.r.t. Delay A. See Figure 4. With the the notch filter in the circuit, the real part of the open loop response is negative and symmetric which implies that when the loop is closed, we get damping. These results are shown in Figures 5 at 150 GeV and Figure 6 at 980 GeV.

To test whether the dampers indeed work, we excite the beam at 980 GeV by switching the sign of the gain. This is a good sign because we can actually excite the beam which means that there is sufficient gain in the loop. When we switch the sign of the gain back to damping, we find that the excitation can be damped. The results of these actions are shown in Figure 7. Although the dampers do perform their job, we find that damping takes 2 to 3 minutes in this example.

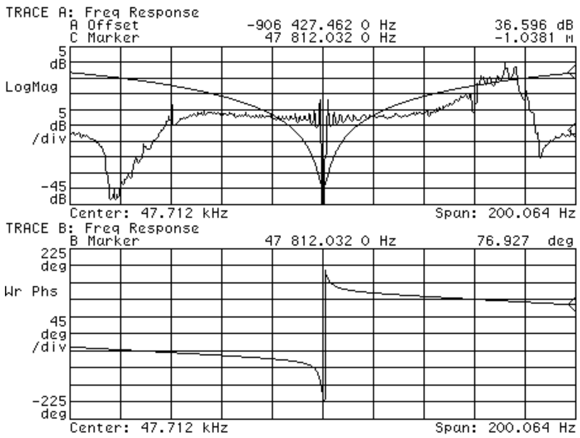

Figure 4: With both delays in the loop, we get notches near the revolution harmonics. The uncorrected imaginary response with one digital delay is superimposed for reference.

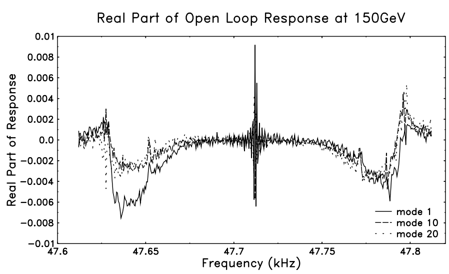

Figure 5: This graph show the real part of the open loop response of modes 1, 10 and 20 at 150 GeV. We have superimposed all the three graphs on top of each other by shifting the frequency of mode 10 by $-10f_0$ and mode 20 by $-20f_0$.

CONCLUSION

After installing the dampers, the problem of sudden beam size growth during a store discussed in *Introduction*, is no longer observed. To prove to ourselves that the dampers definitely stopped the problem, we deliberately turned the dampers off for one store. In this store the beam blew up longitudinally as before. This conclusively showed us that the longitudinal dampers solved the problem. However, the underlying cause of the blowup is still not understood. There are speculations that higher order parasitic modes in the RF cavity, phase noise from microphonics etc. are the source of these blowups. For intellectual satisfaction, a hunt for the source will be the next thing to do. However, operationally, the dampers are a success.

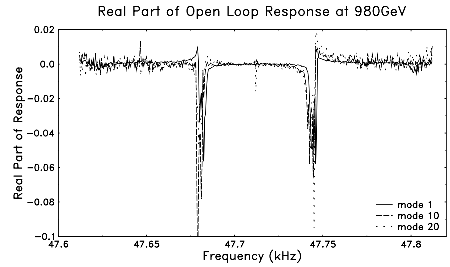

Figure 6: Similar to Figure 5 but at 980 GeV.

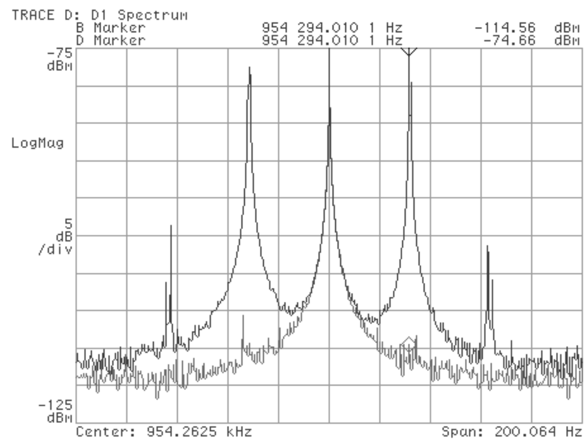

Figure 7: When we closed the loop at 980GeV, we excited the beam by anti-damping it. Then we turned on damping and clearly the synchrotron lines of mode 20 were damped.

REFERENCES

[1] C.Y. Tan, J. Steimel, "The Tevatron Bunch by Bunch Longitudinal Dampers" (unabridged), Fermilab Technical Memo, TM-2184.

[2] A.W Chao, "Physics of Collective Beam Instabilities in High Energy Acceleratorsg", Wiley Series in Beam Physics, 1993.