HOM RF Cavity Dampers for Suppressing Coupled Bunch Instabilities in the Fermilab Booster

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Abstract

The coupled bunch mode n=16 longitudinal instability observed in the Fermilab Booster has been successfully damped by installing a set of passive higher-order mode (HOM) dampers in the 17 Booster RF cavities. The Booster is a fast cycling 8 Gev proton synchrotron with harmonic number 84. The dampers remove energy from two cavity modes at 165 and 217 MHz. The addition of these dampers to the RF cavities has reduced the longitudinal emittance of high current beams at extraction by a factor of 3. The mode dampers will be described along with beam spectra and data showing the longitudinal emittance reduction.

I. INTRODUCTION

Longitudinal coupled bunch oscillations of bunched beams are often observed in circular accelerators as beam intensities are increased.[1-3] Depending on the growth rate of these instabilities, the amplitude of the oscillations may become large and lead to longitudinal emittance growth due to the nonlinearity of the RF bucket. In the case of the Fermilab Booster, large coupled bunch oscillations are observed to occur after transition for bunch intensities greater than 1.5 x 10^{10}ppb.[4] The upper curve in Fig. 1 shows the longitudinal emittance growth through the Booster acceleration cycle without damping for an intensity of 2 x 10^{10}ppb. Values of longitudinal emittance were calculated from measured bunch lengths taken from a wideband resistive wall current monitor.

Coupled bunch oscillations can be stabilized by either increasing the spread in synchrotron frequencies, actively damping the longitudinal motion of each bunch, or reducing the impedances of the resonators responsible for the bunch to bunch coupling. In the case of the Fermilab Booster, the third method of reducing the coupling impedances was chosen because of its simplicity, low cost, and reliability. With this choice the problem could be simplified into three steps: 1) identifying the offending modes in the beam current spectrum, 2) finding the specific higher order RF cavity modes responsible for the coupling, and 3) building a set of HOM dampers to remove energy from the RF cavity higher order modes.

II. IDENTIFYING THE COUPLED BUNCH MODES

Using the same notation as Sacherer[5] for a narrow band resonator at a frequency, f_{res}, the coupled bunch mode number n is excited when:

$$f_{res} = \text{integer} \times Mf_o \pm nf_o$$

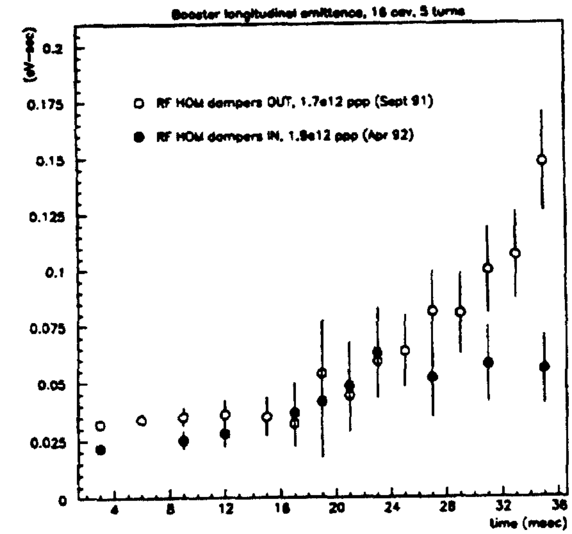

Figure 1. Longitudinal emittance (eV sec) as a function of time (ms) in the Booster cycle with and without HOM dampers.

Here f_o is the Booster revolution frequency and M is the number of bunches which in our case is equal to the harmonic number h=M=84. Figures 2 and 3 show FFTs of the beam current signal taken from a wideband resistive wall monitor using a Tektronix DSA602 digital signal analyzer. The beam current was sampled at 35 ms into the Booster cycle when the coupled bunch oscillations were fully developed. The FFT shows the harmonics of the RF frequency separated by the 84 coupled bunch lines. The dominant coupled bunch mode lines are seen to occur at n=16 and n=36. The individual bunch motion is predominantly a dipole oscillation. FFT beam spectra taken at 2 ms intervals throughout the acceleration cycle show both the n=16 and n=36 mode structure appearing shortly after transition. The n=16 mode reaches a maximum amplitude at approximately 10 ms before extraction and remains constant or decreases slightly. The amplitude of the n=36 monotonically increases after transition reaching its maximum value at the extraction time.

III. HIGHER ORDER RF CAVITY MODES

The HOM of the RF cavities were suspected of providing the coupling between bunches since removing four of the RF cavities resulted in a decrease in the longitudinal emittance growth.[4] The Booster has a total of 17 double gap ferrite tuned cavities.[6] Each cavity consists of two back to back quarter wave coaxial transmission line sections. The electrical length between the two gaps is 140° at the fundamental frequency. The search for the RF cavity modes associated with the beam coupled bunch spectra began with a measurement of the resonant frequency f_{res} of each HOM. Since the fundamental frequency of the cavities $f_{rf}=hf_o$ must

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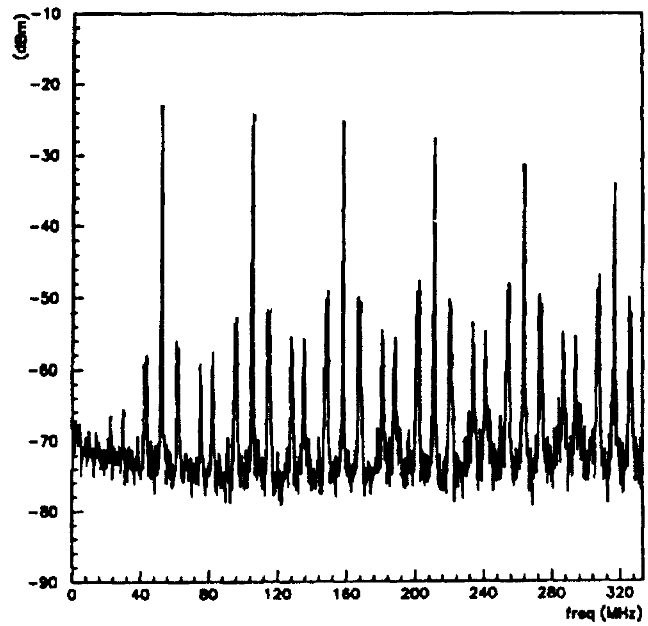

Figure 2. FFT of Booster beam current signal at 1.3 x 10^{12} ppp without HOM dampers.

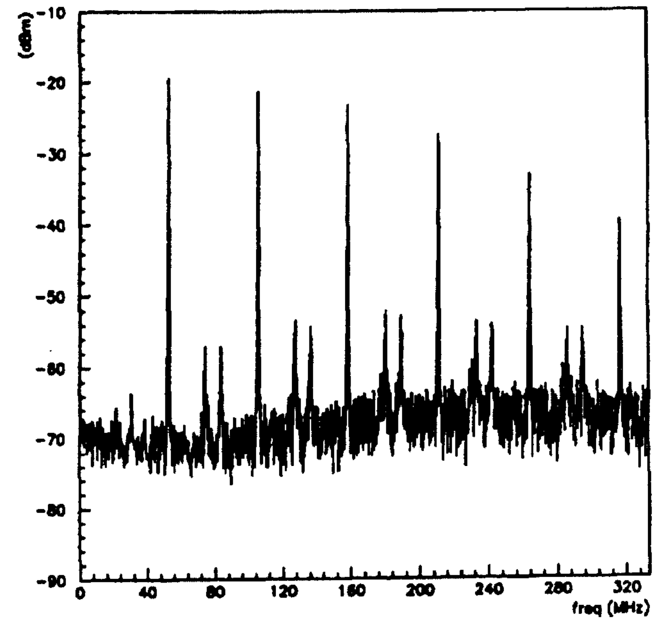

Figure 3. FFT of Booster beam current signal at 1.9 x 10^{12} ppp with HOM dampers installed.

sweep from 30 MHz to 52.8 MHz, the majority of the HOM's also tune during the acceleration cycle. The frequency measurements were made on a spare Booster cavity using an RF network analyzer. By varying the bias current to the ferrite tuners on the cavity the HOM spectrum could be measured as a function of the cavity fundamental frequency. This information was then used to calculate the mode number of each HOM as a function of time during the acceleration cycle. One cavity mode at 83 MHz did not tune with ferrite bias current. However, at the extraction energy this mode corresponds to a mode n=36.

$$f_{res} = 2 \times 84f_o - 36f_o = 83 \text{ MHz}$$

An examination of the tunable modes showed two that pass through mode n=16 after transition. The first mode tunes from 127 to 169 MHz while the second mode tunes from 202 to 221 MHz. In all three modes the two cavity gaps oscillate in phase. The impedances of these modes were measured on the test cavity using a standard stretched wire technique. The impedances measured were Z=10kΩ at 83 MHz, Z=2.3kΩ at 165 MHz, and Z=16kΩ at 217MHz.

A complete set of measurements were also made of the beam excitation of the HOMs for each of the 17 Booster RF cavities. A signal from a calibrated, capacitively-coupled, gap voltage monitor from each cavity was fed to the input of an HP8568B spectrum analyzer. Sweeping the spectrum analyzer from 100Hz to 400 MHz and using the maximum hold feature of the instrument, a beam-induced spectrum was obtained over a period of several hours. After the spectral peaks had been identified, the center frequency of the analyzer was set to the peak of each resonance in the zero span mode and triggered at the start of each Booster cycle. This produced a time record of the HOM excitation during the cycle. A typical example of this output for the 217 MHz mode is shown in Fig. 4. The amplitude is seen to reach a maximum shortly after transition and then decrease slightly. Data for the 165 MHz mode showed a similar behavior while the 83 MHz mode continually increased after transition. The agreement in the mode numbers between the FFT beam current data and the cavity gap monitor data, along with the same characteristic time dependence, led us to identify these three modes as being responsible for the coupled bunch instabilities.

IV. HOM DAMPERS

The frequency of the non-tunable mode at 83MHz is determined by the physical length of the cavity's drift tube. This mode along with another fixed frequency mode at 79 MHz were already being damped by two coupling loops terminated into 50Ω loads. To increase the damping at 83MHz the loop area was increased with a 0.5" copper spacer and a notch filter was inserted between the loop and the 50Ω

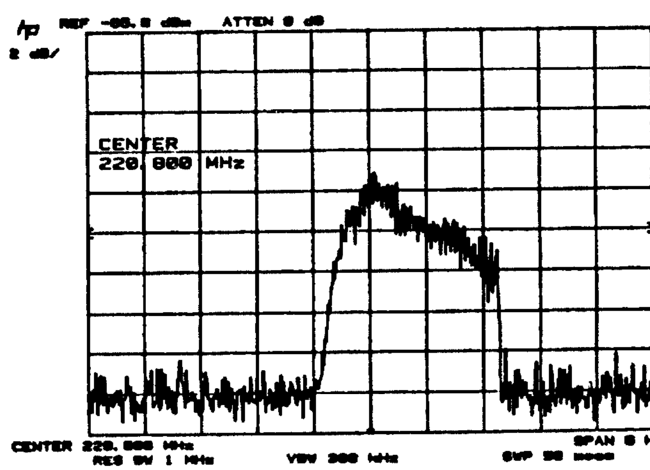

Figure 4. Spectrum analyzer output showing the excitation (2 dB/div) of the 217 MHz RF cavity mode as a function of time (5 ms/div).

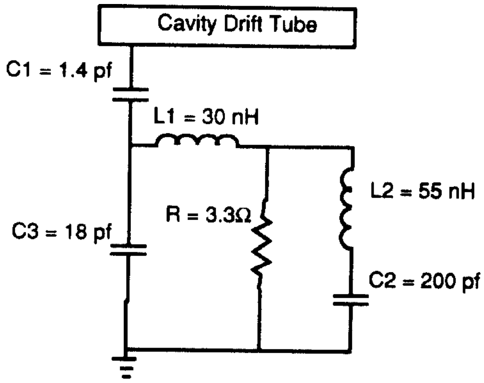

Figure 5. Electrical schematic of 217 MHz HOM damper.

load to reduce the additional power dissipated in the load at the fundamental frequency. This modification produced an additional 10 dB of damping at 83MHz.

The mode dampers for the 165 and 217 MHz modes are similar in design and are installed on only one half of the cavity. They both consist of capacitively-coupled .125" thick x 6" long x 2"(3.5) wide OFHC copper flaps located at a voltage maximum for each mode. The flaps are curved to be concentric with the outer cavity wall and are supported by a 0.5" dia copper rod which is soldered to the center conductor of an HN type connector. The center pin of the HN connector unscrews from the connector body for easy installation of the damping flaps through the side wall of the cavity. The center pin also acts as the inductor L_1 shown in Fig 5. Outside of the cavity the damping flaps are connected to three 10Ω, 40W low inductance resistors in parallel, R, and through a short length of .080" dia copper wire, L_2, to two 100 pf transmitting capacitors, C_2. L_2 and C_2 are adjusted to be series resonant at 48 MHz with a Q of approximately 25. The center value of 48 MHz was chosen to minimize the total integrated power, over the entire acceleration cycle, dissipated in the resistor R at the fundamental frequency. The entire external damping network is enclosed in a 2" x 3" x 5" shielded alumimum box with a 28 CFM all metal fan attached to the box top to provide extra cooling. Under normal Booster operating conditions the added cooling provided by the fan is not necessary; however, with the additional cooling, the dampers have been tested at the maximum Booster cycle rate of 15 Hz.

The 165 and 217 MHz dampers have a bandwidth of 15 MHz and reduce the HOMs by approxiately 20 dB and 25 dB respectively. Fig. 3 is the beam current FFT spectrum taken with dampers installed in all 17 Booster RF cavities. The coupled bunch mode 16 line is no longer present. The reduction in the longitudinal emittance growth with the dampers in place is shown in the lower trace of Fig. 1.

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