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LONGITUDINAL MOTION OF THE BEAM IN THE FERMILAB BOOSTER

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Summary

When the Fermilab Booster Accelerator is operated at or above 1.5 x 10^{12} protons per pulse (extraction current about 155 mA) large amplitude coupled bunch longitudinal dipole oscillations occur between transition and extraction times. The oscillations do not contribute to beam loss in the booster but, because the beam is transferred synchronously into preexisting buckets in the Main Ring,[1] the oscillations contribute to a deterioration of beam quality in the main ring. Two mode numbers have been established for the instabilities and the primary source frequencies have been isolated, although the offending objects have not. Operation of one of the eighteen accelerating cavities at a harmonic number one unit lower than the operating value (83 instead of 84) effectively damps the motion by the introduction bunch to bunch synchrotron tune spread.

Booster Longitudinal Instability

In Figure 1 the position of three adjacent booster bunches within their buckets is shown for three milliseconds preceding extraction. (Time proceeds down in the picture and the traces at the bottom occur after extraction). The sweep rate in the figure is 5 nsec per division and the peak bunch oscillation amplitude is apparently near 45 degrees. The rate of change of the guide field at this time is near zero so the oscillations are occurring within large, nearly stationary, buckets. It is convenient to keep the rf voltage relatively high at this time in the booster cycle so that the coherent synchrotron motion can be sufficiently rapid to facilitate effective phase-lock with the main ring injection frequency previous to synchronous transfer.[1]

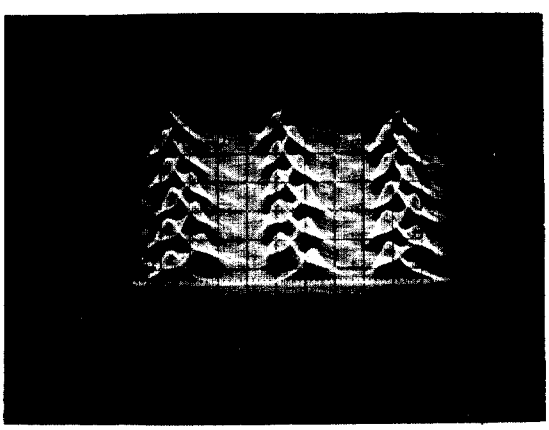

Figure 1. Coherent dipole bunch oscillations for three adjacent bunches during the last three milliseconds of Fermilab booster acceleration. Sweep rate is 5 nsec per div.

In Figure 2 the frequency spectrum of the circulating bunches is shown on a scale of 50 MHz per division. The amplitude scale is linear and the data were taken during the same time span as in Figure 1. The first 5 harmonics of the fundamental rf frequency (52.8130 MHz) are clearly evident. Clearly visible also are first order frequency modulation sidebands separated from the harmonics of the fundamental frequencies by approximately ±21 MHz. Near the higher harmonics there also appears a second set of FM sidebands separated from the harmonics by approximately ±11 MHz. The appearance of the second set of sidebands only near higher harmonics may be misleading in that the spectrum analyzer is observing that part of the spectrum later in the acceleration cycle where the second instability has grown in amplitude. If the analyzer is triggered later the 11 MHz sidebands appear with observable amplitudes near the fundamental and lower harmonics. Large dipole bunch motion together with the spectral density distribution shown are consistent with the presence within the ring of one or more resonant objects with realtively high Q and attendant high shunt impedance and narrow bandwidth.[2,3] Examination of any region of the spectrum with higher resolution will reveal, of course, that each of the harmonics and their sidebands have additional, more closely spaced sidebands, associated with coherent synchrotron motion.

Examination of more specific and detailed data has indicated that two longitudinal modes with mode numbers 16, and 33 or 34 are present. The phase shifts between neighboring bunches for the two modes are near 70 degrees and 145 degrees respectively. The mode number 16 motion, with 11 MHz sidebands, apparently grows more slowly and is associated with a resonant object with higher Q than the mode 33/34 motion.

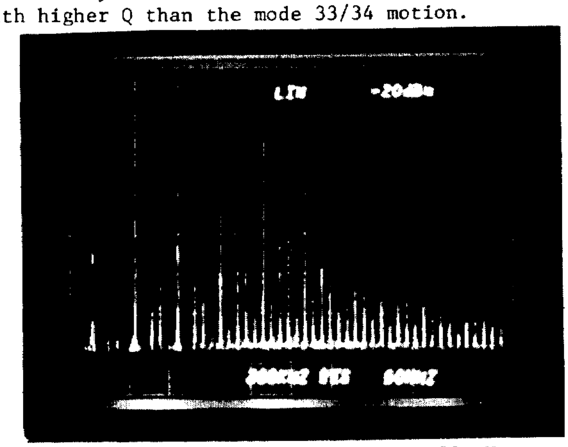

Figure 2. Beam signal spectrum, 50 MHz per division, during bunch oscillations shown in figure 1.

Identification of Specific Instability Frequencies

Discrete spectra of harmonic sidebands can arise from the presence in the ring of objects which appear to the beam as high Q resonators with high shunt impedance. Such resonances are frequently spurious resonances in the accelerating cavities, but a large number of other objects can interact unstably with the beam. Resonant structures other than those associated with the accelerating cavities will probably have frequencies which reamin fixed during the accelerating cycle. Spurious resonances in the rf cavities are likely to tune to some extent as the cavities are tuned through the accelerating cycle (30.1 to 52.8 MHz) although certain of the cavity resonances also reamin fixed.

In an attempt to isolate the specific frequencies

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being excited by resonant objects, detailed examination of instability spectra were made with the booster operating at two different final energies, 4 GeV and 8 GeV. At 4 GeV the rf frequency at extraction is reduced from 52.8130 MHz to 52.150 MHz. If there exists a fixed frequency resonator which is responsible for an instability, a change in the rf frequency during the slowly changing field period just pervious to extraction will result in a change in the harmonic sideband realtionship over the entire spectrum. Only one frequency, that of the offending resonator, will remain fixed. By examination of the location of sidebands at the two final energies, frequencies which reamin fixed can be localized even if they are not within the spectral range examined.

At 8 GeV the more closely spaced FM sidebands are spaced 10.31 MHz from harmonics of the fundamental rf frequency. Upon reduction to 4 GeV these sidebands are found to have moved away from the harmonics to a spacing of 14.95 MHz. This relatively large increase implicates an upper sideband of a high harmonic. An upper sideband of the 7th rf harmonic at 380 MHz meets the requirement of remaining fixed for both operating energies. There are indeed strong spectral lines at 380 MHz for each operating condition but no resonant object or spurious cavity resonance has been located at that frequency.

The remaining family of sidebands is found to decrease in spacing from 21.2 MHz at 8 GeV to 19.15 MHz at 4 GeV. This change implicates the lower sideband of the third harmonic, at 137.3 MHz. Figure 3 shows the major features of the beam spectra at 4 and 8 GeV with the line at 137.3 MHz remaining unchanged. Again there has been no clear identification of the offending resonant structure.

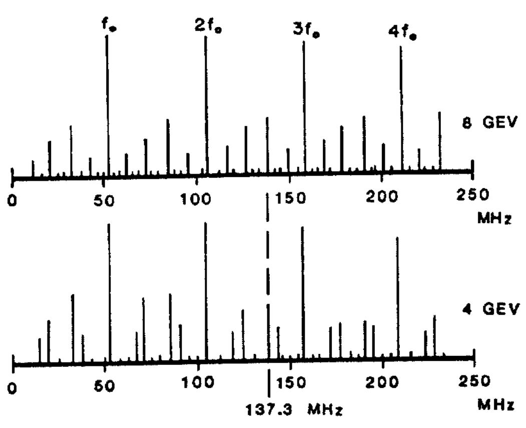

Figure 3. Location of the families of largest spectral lines associated with longitudinal bunch motion for final energies of 8 GeV and 4 GeV. The sideband at 137.3 MHz reamins fixed at each energy.

alternative methods of damping the motion must be employed. In order to minimize the bunch to bunch coupling by a form of Landau damping one of the eighteen accelerating cavities is operated at harmonic number 83 instead of 84 following transition, thus introducing a small bunch to bunch synchrotron tune spread.[4,5]

In order to make the best use of available rf cavities the cavity which is used to introduce damping is used for normal acceleration until slightly beyond transition at which time it is switched one harmonic number down in frequency. Figure 3 is a block diagram showing how the 83rd harmonic rf voltage is developed and delivered to the power amplifier coupled to the damping cavity. The rf drive signal to each amplifier is gated on by a dc signal delivered to a balanced mixer. If, instead, the balanced mixer is driven by a sinusoid at the booster rotation frequency, it acts as a balanced modulator, developing upper and lower sidebands while suppressing the input driving frequency. The rotation frequency is obtained by scaling the rf source frequency by half the harmonic number with a fast recycling scaler. The scaler output pulse train is delivered to a single flip-flop which creates a square wave of the desired frequency which is then filtered. The resulting sideband rf outputs are then at harmonic frequencies h = 83 and h = 85 separated by 1.257 MHz. These signals are delivered simultaneously to the power amplifier. The damping cavity, which has a Q of 1100 at this frequency, is tuned to select the lower sideband following the change in gating. The phase-feedback tuning system for the cavity is disabled during the transition period and upon being re-enabled tunes the cavity normally at the 83rd harmonic. Figure 4 is a block diagram showing the manner in which the upper and lower sidebands of the fan-out rf are generated for the rf station selected to do the damping. In Figure 5 the rf envelope of the damping cavity is shown throughout the entire accelerating period. The rate at which the transition is made between harmonics is limited by the current slewing capability of the Ferrite Tuning Bias Supply.

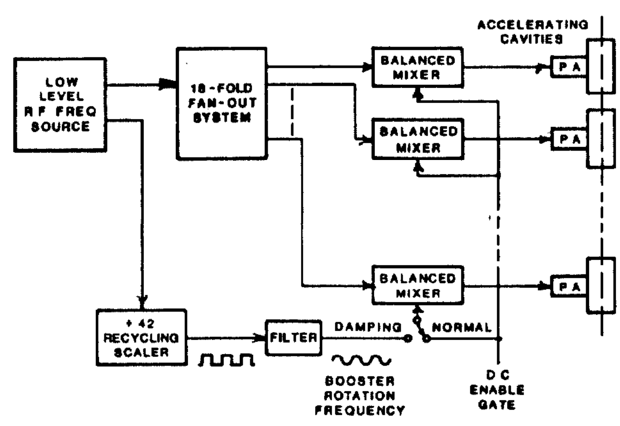

Figure 4. Block diagram of procedure for producing an rf drive signal to a single station with harmonic number 83 instead of 84.

Longitudinal Motion Damping

The coupled bunch motion described above could be reduced in amplitude or cured by locating the objects which are developing the associated longitudinal fields and removing them from the ring or modifying them so that the fields cannot be developed. Since there is some difficulty in locating the perturbing objects,

The use of one of eighteen cavities for damping allows a maximum change in accelerating voltage during each revolution of only about 12 percent or a 6 percent change in coherent synchrotron frequency. This amount of tune shift is sufficient to reduce the amplitude of coupled bunch motion to an acceptable level, as shown in Figure 6 as compared to Figure 1. Operation of one accelerating cavity in this mode is now a normal proced-

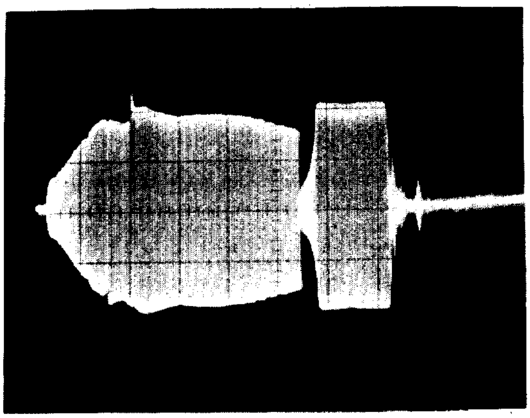

Figure 5. RF envelope of the rf station selected for damping. Sweep rate is 5 msec per division and the station is switched from acceleration to damping at 25 ms after the start of acceleration.

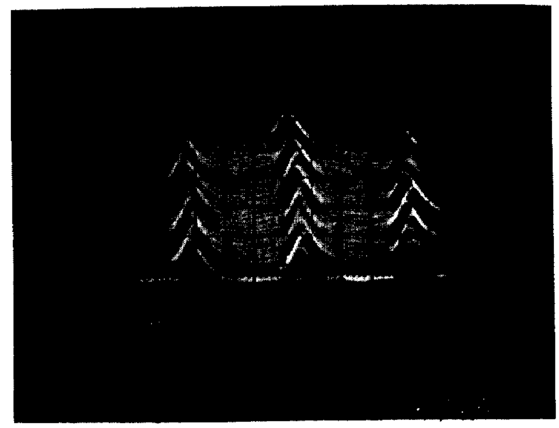

Figure 6. Coupled bunch motion under the same conditions as figure 1 but with damping rf station operating.

ure. Initiation of this procedure resulted in an immediate improvement in the Main Ring beam transmission and in the quality of beam extracted from the main ring.

References

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