REAPPEARANCE OF LINAC BUNCH STRUCTURE ON
BOOSTER BUNCHES DURING CAPTURE AND ACCELERATION

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Summary

During adiabatic capture and initial 30 MHz beam bunching in the Fermilab Booster very high frequency structure is observed on the bunches. The structure has the appearance of a bunch shape oscillation instability which appears and disappears in a sporadic manner. A computer simulation of injection dynamics reveals the fact that the observed structure is related to re-appearance of the injected linac bunch structure after relocation within the booster phase space.

Introduction

In the present mode of operation the Fermilab Booster is filled with a single turn of beam from the 200 MeV Linac. The 204 MHz linac bunch structure debunches within a few turns and the beam is adiabatically captured in 30.1 MHz buckets for subsequent acceleration. To avoid multipacting, booster rf stations are turned on in advance of beam injection at a voltage level sufficient to create the required bucket area but with adjacent pairs of cavities out of phase with each other (or "paraphased"). In order to raise the voltage adiabatically following injection the phases of adjacent cavities are rotated toward each other under program control in the manner which yields optimum capture. The injection bucket is completely formed in about 100 nsec or about 36 turns. The time at which "orthophasing" of the rf is started can be delayed with respect to injection up to about 50 turns. This delay is also adjusted to optimize capture efficiency.

The process of adiabatic capture and formation of 30 MHz bunches has been studied extensively using "bunch locked" mountain range displays of the beam current as developed on a broad-band (~1 GHz) resistive beam current detector. In these studies very high frequency oscillations are frequently observed to be superposed on the forming bunches. The signals have the appearance of a longitudinal instability which grows very quickly, typically within two turns (about 6.5 nsec), then disappears as quickly. The signals may reappear in similar fashion, perhaps 15 turns later and at varying periods during subsequent acceleration.

Signals indicative of frequencies between 300 and 800 MHz have been observed. The apparent frequency, time of appearance, and other features of the phenomenon are strongly affected by the adjustment of the Linac de-buncher cavity and details of the Booster rf turn-on program. Attempts to follow the phase of such a disturbance from one bunch to the following bunch are always unsuccessful indicating that the effect is probably not a "coupled bunch" instability.

The presence of a series of "paraphased" pairs of accelerating gaps presents the possibility of a weak "longitudinal strong focusing" effect before and during the early part of adiabatic capture. This and other effects associated with variations in the rf

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turn-on procedure have been studied in a computer simulation of the rf capture procedure. The program is capable of examining the motion of an ensemble of injected particles within a single bucket for a variety of rf gap locations, voltages, and phases. Data are presented showing the time development of particle locations in the phase space and a projection of the particle density on the longitudinal axis. Because the program is limited to following a few hundred particles (400 or 800 in the examples shown) the density projection, representative of the bunch shape, suffers somewhat from statistical fluctuations of particle numbers within the bins. The 2 π radian phase space is divided into 50 bins, a compromise between bin statistics and resolution. The calculations represent only stationary buckets during injection and capture with no acceleration component.

A computer simulation of the motion of injected protons into developing rf phase space appears to provide a satisfactory explanation for the observed structure. While the injected linac bunch structure would be expected to debunch quickly due to the injected momentum spread (~0.1 percent) the linac bunches actually maintain their integrity within the developing booster phase space and at intervals of half a synchrotron period they become "vertical" within the phase space and create anomalously large current peaks within the booster bunches giving the appearance of a longitudinal instability.

Bunch Shape Development During rf Capture

Figure 1a shows the evolution of charge distribution within several 30 MHz buckets during the first thirty-six turns following injection. In the figure, time progresses upward and traces were taken on alternate turns, always locked to the same rf phase location on the orbit. In this instance the rf cavities remained paraphased for the first eight turns. Clear evidence of the 204 MHz linac bunch structure can be seen on the first turn but it has completely disappeared by the third turn. Smooth development of 30 MHz bunches proceeds until the twenty-fifth turn when within two turns a very high frequency signal is apparent on the bunches. The signal is attenuated somewhat on following turns but reappears on the thirty-fifth turn. Figure 1b is a single turn trace of the twenty-fifth turn showing well developed spurious signals superposed on the bunches. The sweep rate is 10 nsec per division and the superposed signal has a period indicating a frequency near 430 MHz. (In these data VHF frequencies are delayed slightly in time with respect to the 30 MHz signals because of the 250 MHz bandwidth of the oscilloscope used to record the data).

Figure 2 is a mountain range display of the first thirty-six turns following injection taken under the same conditions as Figure 1 except that "orthophasing" of the rf voltage has been started immediately following injection. Spurious signals can be seen on bunches at the eighteenth turn and the apparent frequency is slightly lower than that shown on Figure 1. Spurious signals similar to those shown can be observed with varying apparent frequency, amplitude, and time of appearance for almost any combination of rf turn-on

procedure and injected momentum spread.

Figure 1 a) Development of 30 MHz bunch structure during first thirty-five turns following injection. Apparent instability is visible on twenty-fifth turn. Onset of rf bucket development is delayed for ten turns. b) Detail of structure on twenty-fifth turn.

Figure 2. Bunch structure development during thirty-five turns with no delay in start of bucket development.

Computer Simulation of Injected Bunch Evolution

In the first series of simulations the evolution of a linac beam with momentum spread of 0.08 percent and a bunching factor of five is presented. Eight accelerating gaps of 25 kV each are introduced at locations 45, 46, 48, 49, 70, 71, 73, and 74 out of a possible 84 locations. (The harmonic number of the booster is 84). The gaps are initially paraphased in pairs and they are brought into phase with each other linearly between the first and the twenty-eighth turn. In Figure 3a the injected particle distribution within a single bucket is shown after one turn. The projection of the particle density clearly shows evidence of the 204 MHz linac bunch structure. Figure 3b shows the same distribution at the end of seven turns. The projected density shows a small amount of 30 MHz bunching but evidence of the linac bunch structure has disappeared. Figure 3c shows the same distribution at the thirteenth turn. At this point linac bunches which started near the center of the phase space have completed about half of a synchrotron oscillation and segments of the linac bunches have again become vertical. Projection of the density shows 30 MHz bunching and the inverted linac bunches clearly create

Figure 3. Computer simulation of phase space population following injection on the turns 1, 7, 13, 16, and 21.

peaks in the projection. If the entire phase space represents one 30 MHz period of 33 nsec the average peak spacing within the bunch is approx. 2.9 nsec corresponding to a frequency of 345 MHz. In part d of the figure the distribution is shown three turns later and the spurious periodicity on the projection is largely washed out. However, by the twenty-first turn, Figure 3e, particles near the center of the bucket have completed one synchrotron oscillation and segments of the linac bunches have again become vertical, creating distinct peaks in the current projection. It is evident that if the phase spread of the 30 MHz distribution becomes smaller due to excessive rf voltage or bucket area the apparent frequency of the spurious signals will increase at each reappearance.

It would seem that this effect might be reduced or eliminated by allowing the injected linac beam to drift for a reasonable time before starting adiabatic capture. This would almost certainly be effective if the elapsed time could be sufficiently long to allow a spread of the injected bunches over several of the 30 MHz phase spaces. In the Fermilab booster, however, the injection time is limited to about 150 nsec, or 45 turns, by the 15 Hz sinusoidal guide field variation.

The effect of short delays is shown in Figure 4. Figure 4a shows the linac bunch spread after seven turns during which no net bunching voltage is applied. The charge projection shows no meaningful structure even though the phase space population is still organized. Linac bunches have spread longitudinally spanning about π radians of the 30 MHz phase space. Starting at turn seven the rf gaps are brought into phase 4b the distribution is shown at turn fifteen where evidence of 30 MHz bunching is present but no structure appears. At turn eighteen, Figure 4c, linac bunch segments are vertically aligned creating clear structure on the 30 MHz bunches. The apparent frequency in this instance is near 619 MHz. The effect of delaying the start of the bunching process with other parameters being held equal has been to increase the apparent frequency of the spurious bunch structure. As before, the spurious structure will disappear within one or two turns and reappear after another half synchrotron period and at subsequent half periods with some obscuration due to synchrotron tune-spread

Conclusions

The sporadic appearance of very high frequency structure on developing booster bunches is apparently not the result of a dynamic instability, but simply a consequence of the initial phase space population of linac bunches. Nevertheless, there may be a serious disadvantage associated with the effect. There is evidence that one factor limiting booster intensity is incoherent space-charge betatron tune shift which will be exacerbated by the high peak currents associated with the spurious structure. Because of booster bunch width reduction early in the acceleration cycle the peak currents developed may actually exceed those which are injected by the linac.

While it is difficult to eliminate the observed effect entirely, it can be minimized by careful attention to rf turn-on procedures and particularly to the degree of rf cancellation previous to adiabatic development of buckets.

Finally, it is noted that during this study, at a time when imbalances in rf cancellation previous to capture were intentionally introduced, bunch shape distortions were noted which were strikingly similar to those reported by Gumowski and Zanaschi¹ in discus-

Figure 4. Computer simulation of phase space population following injection on turns 7, 15, and 18. Onset of bunching rf is delayed until after the seventh turn.

sion of bunch shape oscillation during rf capture in the CERN PS Booster. Figure 6 of this paper, showing bunch shape distortion about fifty turns after injection, is to be compared to figure 4a of the cited paper.

Figure 6. Bunch shape distortion fifty turns after injection with rf voltage imbalance previous to start of adiabatic capture.

References

1. I. Gumowski and D. Zanaschi. Bunch Shape Oscillation Control in RF Trapping, IEEE Trans. on Nucl. Science **NS-22** No. 3 p 1847 (1975)