OBSERVATIONS OF A LONGITUDINAL COUPLED BUNCH INSTABILITY IN CESR[†]

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Abstract

During the last several years of operating with trains of bunches, a longitudinal dipole coupled bunch instability has been observed at the Cornell Electron Storage Ring (CESR). Without the use of multibunch longitudinal feedback this instability would limit the total stored current in the two beams during High Energy Physics (HEP) operation. This paper gives an updated report on observations of this instability, its strength, its dependence on bunch spacing within in the trains, its relationship to changes made in the RF accelerating system and results of simulations using the observed mode spectra of the RF cavities.

1 INTRODUCTION

Since February of 1995 during HEP, CESR has operated with angle crossing collisions of two beams (electrons and positrons) with 9 nearly equally spaced trains of 2 to 4 bunches per train.[1] The spacing between lead bunches in the trains is either 280 ns or 294 ns and the bunch spacing within the train occurs in multiples of 14 ns with a maximum train length of 56 ns. When the longitudinal feedback is not employed for beam stabilization and at currents above 200 mA in a single beam or 300 mA in two beams, a dipole longitudinal coupled bunch instability may occur.

As reported earlier[2] a number of effects are associated with the instability which may be observed with either positrons, electrons or both beams. The instability threshold is defined as the current at which the amplitude of the synchrotron sidebands in a beam position monitor's spectrum begin to grow rapidly in amplitude vs. current. This effect is often a 6 dB increase in amplitude for a few percent change in current. The dipole oscillations of the bunches appear to self-limit above the instability threshold, but the amplitude of the oscillation grows as current increases until at a higher current quadrupole coupled bunch oscillations are observed both in the frequency spectrum and recently in the bunch shape oscillations observed by a streak camera.[3] Over long times the instability threshold currents can vary by as much as 10-15% with no intentional change in operating conditions. The onset of the instability is a function of the number of bunches within the trains and of the spacing of the bunches within the train. Horizontal displacement of the beam within the 500 MHz normal conducting RF (NRF) accelerating cavities alone or changing the cavity temperature make small, but repeatable, differences in the threshold current. These cavities also have higher order modes with damping times longer than the spacing

between trains. From these observations it is concluded that the impedance of the NRF cavities plays a significant role in the instability.

During operations a longitudinal bunch by bunch feedback system and a narrowband feedback system (which stabilizes the lower synchrotron sideband of the first rotation harmonic) are in routine use.[4] The wideband longitudinal feedback system drives a stripline kicker and stabilizes the coupled bunch instability which can manifest itself as different synchrotron sidebands becoming unstable depending on the pattern of bunches filled. The narrowband feedback uses the NRF cavities as a kicker and is important at the highest currents to stabilize the coupled bunch mode of oscillation which is destabilized by the detuning of the NRF cavities needed to compensate beam loading. The feedback systems provide sufficient damping to store a total current in the two beams well in excess of the 550 mA HEP operating levels.

2 RECENT OBSERVATIONS

The systematic replacement of NRF cavities with superconducting RF (SRF) cavities[5] during the last two years has made it possible to examine the effect of the NRF cavities on the beam's stability. At the time the longitudinal instability was first observed there were four 5 cell NRF cavities installed in CESR. In October of 1997 two NRF cavities were removed and an SRF single cell cavity and a fifth 5 cell NRF cavity were installed. In November of 1998 this fifth NRF cavity was removed and a second SRF cavity was installed.

Before and after these changes to the accelerator's impedance, the instability thresholds for positrons alone in positron injection conditions and for both electrons and positrons in electron injection conditions were measured with the longitudinal feedback system off for a number of the different bunch spacings with 9 trains. Positron injection conditions maintain a flat injection orbit while the electron injection conditions use electrostatically separated orbits for the counter-rotating beams. Figure 1 shows the results of these threshold measurements. Note that in the data for 4 NRF cavities there are bunch patterns that have much higher thresholds than for the other patterns of bunches. Presumably for these bunch spacings there were modes in the cavities which were destructively interfering. As the NRF cavities were exchanged with SRF cavities there is not as large a variation in the thresholds for different bunch patterns. Since the impedance of the single cell SRF cavities is much lower than the five cell NRF cavities and the higher order modes of the SRF cavities have much lower Q's, one would generally expect the instability would weaken and the thresholds should increase. Although this trend is visible for some patterns, it is not at all dramatic even in these cases.

3 RF SYSTEM MEASUREMENTS AND SIMULATIONS

During the last two years measurements of the properties of the modes of the NRF cavities were made using single 5 mA bunches of positrons. Each of the NRF cavity cells has a field probe installed and, since only one of

these is used for field regulation, the signals from the remaining probes could be observed with a spectrum analyzer. These signals contain a line spectrum at the rotation frequency of CESR and their spectral envelopes give the RF spectrum of the cavity times the coupling for the probes. Spectral data was acquired at times corresponding approximately to the times when the threshold measurements were made.

The spectral data was analyzed to find peaks which were greater than 6 dB above the surroundings and these were fit to a resonance plus a linear baseline. Modes computed by both URMELT and SUPERFISH were used to guide the identification of the different spectral peaks by frequency. Spectral peaks from all the cells in one NRF cavity were compared to select the best fits for each passband member. Then under the assumptions that each passband member could be identified with a particular cell and each would have the same R/Q as a single cell, the ratio of the fitted maximum spectral amplitudes divided by the fitted Q's were compared for peaks in a neighborhood of the passband. Since this ratio is proportional to the R/Q times the coupling coefficient of the probe, the same mode in different cells will have nearly the same ratio. Lastly the peaks for which this ratio changed when the beam was displaced in the cavities were identified as dipole (or higher) modes. From this analysis a set of TM0 passband members for each of the NRF cavities were identified as having the fitted frequencies and Q's and the R/Q's computed by URMELT.

The results for each of the NRF cavities was used as an input to the program MBI[6] which computes the growth rate of the most unstable eigen mode at 10 mA per bunch for the different possible bunch spacings. The greatest growth rate for each of the time periods of April 97, November 97 and November 98 was $15.4 \text{ sec}^{-1} \text{ mA}^{-1}$, $15.2 \text{ sec}^{-1} \text{ mA}^{-1}$ and $8.6 \text{ sec}^{-1} \text{ mA}^{-1}$, respectively. (These growth rates are comparable to the $14 \text{ sec}^{-1} \text{ mA}^{-1}$ damping rate of the feedback system.) If the natural damping of the beam is the same for all bunch patterns, the instability growth rate and the threshold current will be inversely proportional to each other. For each time period the growth rate for each of the patterns of bunches was divided by the maximum growth rate to give the relative growth rate; likewise the inverse of the threshold current may be scaled by the lowest threshold current for a given time period. The relative growth rates and relative inverse of the threshold currents are plotted for each time period in figure 2 for each pattern. If the NRF cavity impedance dominates the longitudinal dynamics then these two plots should correspond. As is seen in figure 2, the calculations and measurements for April 97 are generally in good agreement, but measurements at later times with fewer NRF cavities in CESR show poorer agreement. It is likely that as the cavities are exchanged, the impedance of the rest of CESR becomes comparable to the impedance of the cavities thereby altering the threshold currents. A second result which points toward this hypothesis is that the calculated maximum growth rates decrease by almost a factor of two from the first to the last measurements, but the threshold currents increase by much less than this in
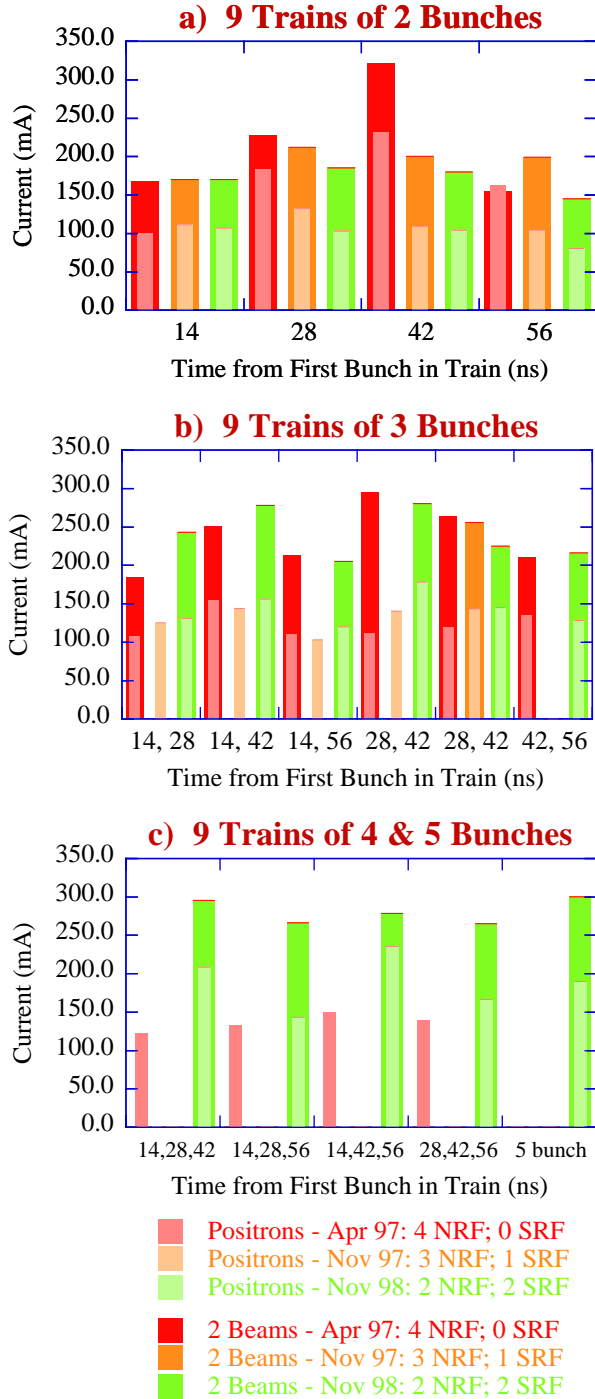

Figure 1. Highest measured instability threshold currents with beam feedback off for different patterns of bunches and different numbers of NRF and SRF cavities in CESR.

a) April 97 Data

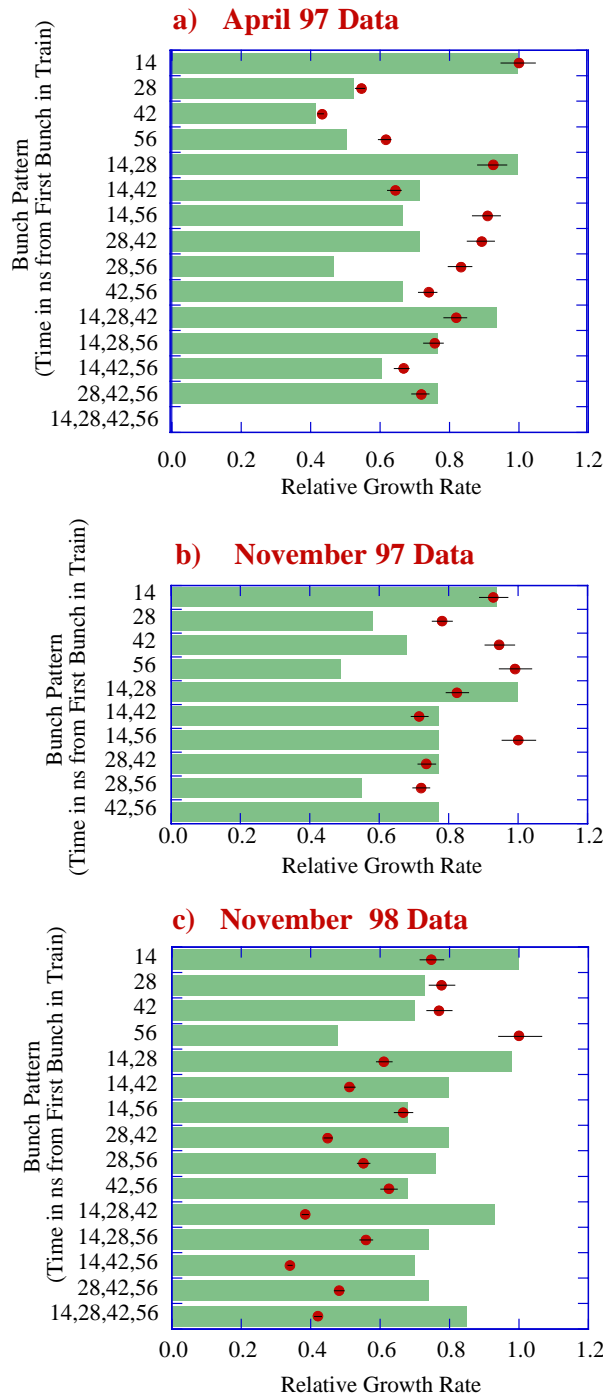### b) November 97 Data

c) November 98 Data

Figure 2. Calculated growth rates for positrons alone relative to the maximum calculated growth rate and the inverse of the corresponding threshold current relative to the lowest threshold current for each time period vs. bunch pattern for 9 trains of 2, 3, 4 and 5 bunches. The bars represent the MBI calculation and the round data points are the inverse of the measured threshold currents for the same pattern. The bunch patterns are expressed as times of subsequent bunches (in ns) relative the leading bunch in the train.

general. Lastly the higher mode loss parameter k for 2 NRF cavities is comparable to the loss parameter for the remaining structures for CESR so it is not surprising that impedance of the rest of the ring would begin to become important in determining the longitudinal dynamics. Calculations by MBI suggest that the instability growth rates for April 97 are dominated by a TM0 passband near 2.7 GHz (just below the beam pipe cutoff.)

4 CONCLUSIONS

The longitudinal coupled bunch instability with trains of bunches in CESR has been observed for the last 4 years. The present longitudinal feedback system has sufficient strength to permit storing much higher currents in CESR than are needed for operations. The NRF cavities have had a major effect on the instability thresholds when the 4 original 5 cell structures were operating in CESR. As the SRF cavities have begun to replace the NRF cavities, the instability thresholds have not in general grown as rapidly as would be expected if the NRF cavities were the only impedance in CESR which contributed to the instability. In March of 1999 the last two 5 cell NRF cavities have been removed and a third SRF cavity installed. Measurements of the instability thresholds will be undertaken once beam is again stored in CESR.

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