COHERENT SYNCHROTRON RELAXATION OSCILLATION IN AN ELECTRON STORAGE RING

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Summary

Detailed observations of the slow fluctuation of the stored beam in the NBS 280 MeV electron storage ring (SURF II) reveal a relaxation-type oscillation, in which brief intervals of dipole mode bunch oscillation alternate with relatively long recovery intervals free of coherent oscillations. A simple phase modulation model of the dipole oscillation shows that an infinite number of modulation sidebands develop around each RF harmonic of the beam. These vary in amplitude as the oscillation grows, giving the appearance of turbulence. The model reveals a self-limiting feedback mechanism which limits the growth of the oscillation. Graphic data illustrating this behavior will be presented.

Introduction

Coherent bunch oscillations in SURF II and attempts to control them have been described at these conferences in the past [1,2]. Recent improvements in injection and capture have raised the beam intensity significantly, with stored currents of 130 to 180 mA at 284 MeV being achieved routinely. At these currents the bunch oscillations are severe and further increases in stored current may be impossible without stabilization. In addition there is growing user interest in fluorescence timing experiments, for which excellent beam stability is a prerequisite.

Earlier attempts at beam stabilization in SURF focused on interaction of the bunched beam with a high frequency resonator, namely the pulse bump coil. Four different structures have been tried over the years. Two were resonant and tuneable to an RF harmonic (the fourth and the second) and two others resonated at frequencies removed from any significant RF harmonic. The tuneable structures did have some effect on the oscillations, but tuning was quite critical. At most, these structures appeared to modify the oscillation threshold, but not the basic mechanism. Higher order modes of the main RF cavity do not appear to be involved either, because none of the higher coaxial quarter wave resonator modes coincides with any significant RF harmonic of beam current.

The only remaining impedance of any significance within the bandwidth of the bunch Fourier spectrum is the RF cavity fundamental mode. It is of necessity strongly coupled to the beam and can drive the Robinson instability [3]. Zotter also points to the fundamental RF cavity mode as a likely participant in longitudinal instability [4].

The bunch oscillations observed in SURF are characterized by a repetitive cycle of exponential (or faster) growth of the n=0 dipole mode of synchrotron oscillation, followed by bunch lengthening, widening and loss of coherence. Each such episode is followed by a recovery or "relaxation" period, free of coherent oscillations and governed by radiation damping. When a threshold for dipole oscillation is reached, the cycle repeats. In the following sections graphic evidence of this behavior is presented, followed by an analysis and suggestion of a self-limiting mechanism.

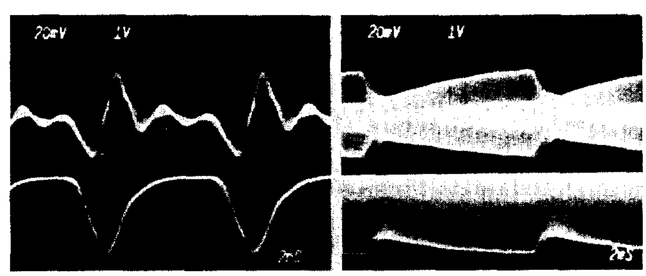
Instrumentation

Most of the waveforms and spectra were obtained from a capacitive beam monitoring electrode (BME), via low-loss coaxial cable, terminated in 50 ohms at the instrument end. This network approximates a differentiator with an RC time constant somewhat less than the risetime of the bunch. Real-time information is also obtained from a crossed-field photomultiplier (XFPM) looking at the synchrotron light through a vertical slit. With a risetime of 120 ps, the XFPM gives a fairly good representation of the longitudinal charge distribution in the bunches and corroborates some of the BME-derived data.

Observations

The upper trace in figure 1a shows a typical BME signal for a beam of about 48mA at 284 MeV, as viewed on a 400 MHz dual-beam oscilloscope at 2 ns/div. Both bunches are displayed. The lower trace is from the XFPM and shows the approximately gaussian light pulses. Both waveforms show evidence of modulation, which is clearly seen when the signals are viewed at 2 ms/div, as in figure 1b. However, the period of the modulation exhibits considerable jitter. To obtain jitter-free traces in subsequent figures, the oscilloscope and/or spectrum analyzer were triggered in single-sweep mode.

The envelope modulation shown in figure 1b, called "slow fluctuation," has been observed at SOR [5,6] in connection with studies of bunch lengthening. Similar modulation has also been observed in NSLS-VUV ring [7]. In the SOR study the fluctuation frequency was found to depend on energy and current. Similar dependence is seen at SURF. The variation with energy is especially wide in SURF due to the 10 MeV injection energy and the 28:1 energy range. The fluctuation period varies by more than three orders of magnitude, from seconds to milliseconds.



(a) (b)

Fig. 1. Beam monitoring electrode signal (upper) and crossed-field photomultiplier output (lower), displayed at (a) 2 ns/div and (b) 2 ms/div, show slow fluctuation.

Figure 2a shows the same BME signal viewed on a spectrum analyzer with a span of 1.8 GHz. The RF harmonics are 114 MHz apart and extend past 1 GHz. Odd multiples of the 57 MHz rotational frequency are visible but their amplitudes are 50 db down, indicating that the two bunches are equally filled to within 0.3%. The spectrum peaks at about the third harmonic due to the frequency response of the RC network.

The RF harmonics have the familiar synchrotron sidebands at multiples of approximately 250 kHz, as seen in figure 2b. There are no sidebands at odd rotational harmonics, which means that the anti-phase (n=1) mode of coupled bunch motion is negligible. Motion of the two bunches must therefore be in-phase (n=0 mode).

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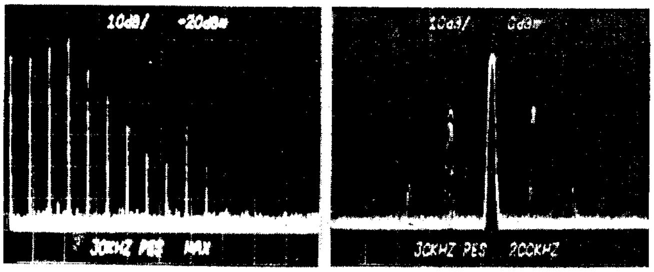

(a) (b)

Fig. 2. Spectrum of BME signal shows (a) 114 MHz RF harmonics to 1 GHz, and (b) synchrotron sidebands around fundamental.

The time structure of the bunch oscillations is analyzed with the aid of the spectrum analyzer operating as a fixed frequency, narrowband receiver. Each RF harmonic and any individual sideband can be observed as a function of time by proper choice of center frequency, timebase sweep speed and receiver bandwidth. All the traces in figure 3 were taken at 2 ms/div and a bandwidth of 30 kHz. Beam currents ranged from 45 to 30mA at 284 MeV. In each case the instrument was in single-sweep mode, triggered by the dip in the BME signal. The RF harmonics are shown in the first column, starting with the fundamental on top. The first few significant sidebands of each harmonic are arranged horizontally.

The striking feature of these oscillograms is the periodic absence of sideband signals, i.e., of coherent bunch motion, during the relaxation phase of each fluctuation cycle. During this phase the amplitudes of the RF harmonics vary slowly, reflecting gradual change in the bunch shape and/or length, due to radiation damping. The first sideband pair appears out of the baseline noise and grows at about 20 db/ms. It stops growing and then collapses rapidly. The higher order sidebands last even more briefly. The entire oscillatory phase lasts about 3 ms. The duration of this phase appears to be much less energy-dependent, but this point has not been studied in detail.

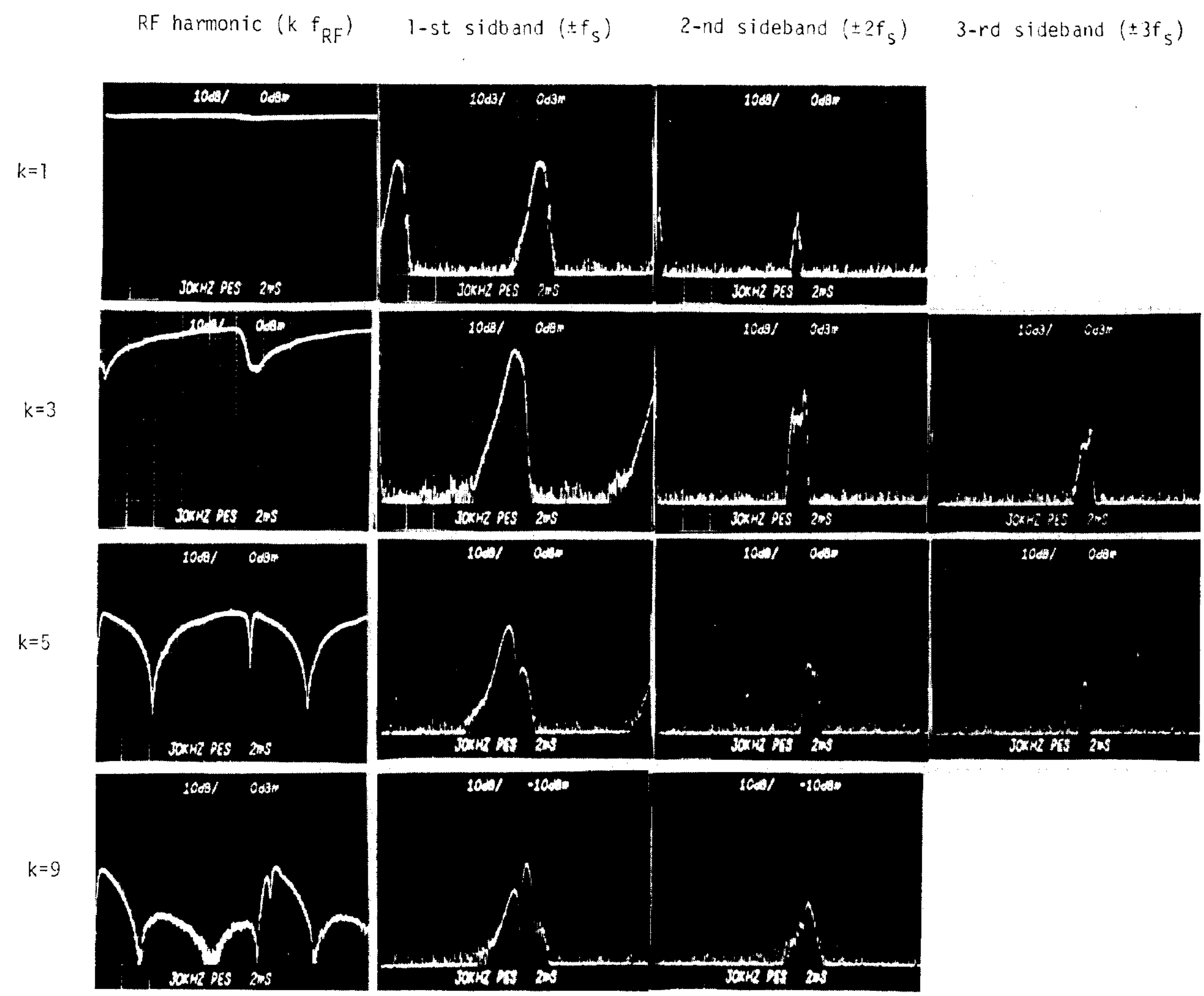

Fig. 3. Time structure of some RF harmonics and principal sidebands of BME signal. Scale: 10 db/div vertical, 2 ms/div. horizontal.

The longitudinal oscillation can be observed by extracting the fundamental (114 MHz) component of the BME signal with a bandpass filter and comparing its phase with a sample of the RF cavity voltage in a phase detector. Figure 4 shows the phase detector output on the upper trace and the unfiltered BME signal on the lower trace, displayed simultaneously on a dual-beam oscilloscope. The beam current here was 45mA at 284 MeV. The growth of the ac component of the phase detector output coincides with the dip in the BME envelope. The frequency of this ac component is about 250 kHz, which agrees with the position of the first sideband pair. Since there is a one-to-one correspondence between the phase of the bunch and the phase of its fundamental component, the observed phase oscillation identifies the motion as dipole mode.

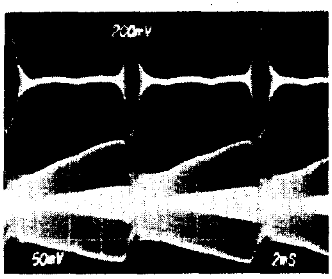

Fig. 4. Phase detector output (upper trace) shows growth of dipole oscillation coincides with dip in BME amplitude (lower trace).

At 284 MeV the threshold of all this activity is about 19mA. Below this level the sidebands become nearly steady-state and disappear entirely below about 17mA. Within this range the dependence of the instability threshold on RF voltage is very apparent: oscillation can be enhanced or suppressed by raising or lowering the RF voltage. As might be expected, the threshold current is also a function of energy.

Analysis

Dipole mode bunch oscillation is analogous to phase modulation of an RF carrier. Communication theory predicts that even simple, sinusoidal, small-angle phase modulation produces an infinite number of sidebands about the RF carrier, at intervals equal to the modulating frequency f_s.[8] One expects to see sidebands at $f_{RF} \pm mf_s$ (m integer) even without invoking the idea of bunch shape modes of oscillation! For peak phase deviation θ_p, the relative amplitudes are given by Bessel functions $J_0(\theta_p)$ for the carrier, $J_1(\theta_p)$ for the first sideband pair, $J_m(\theta_p)$ for the m-th pair, etc. For small θ_p the higher terms are very small and tend to be buried in the noise. If the entire bunch is assumed to be oscillating sinusoidally, the effective phase deviation at the k-th harmonic is multiplied by k. The corresponding amplitudes, relative to the unmodulated k-th harmonic, become $J_0(k\theta_p)$ for the k-th harmonic, and $J_1(k\theta_p)$, . . . $J_m(k\theta_p)$ for the sidebands. Note that small angle modulation at the fundamental translates into large angle modulation at the higher harmonics, with correspondingly larger numbers of significant sidebands appearing around them. Now if θ_p is growing, then all the RF harmonics and their sidebands are varying as Bessel functions of growing arguments. Since Bessel functions go through zeros at large arguments, the higher harmonics and their sidebands will show strong fluctuations throughout the dipole mode growth cycle. Such activity can easily be misinterpreted as "turbulent" or "chaotic."

If the observed oscillation is primarily dipole mode and only the cavity fundamental resonance appears to be involved, the instability is most likely of the Robinson type [9]. However, the usual prescription of detuning the cavity does not always work. With a combination of high cavity Q and large f_s, the synchrotron sidebands fall well outside the cavity passband. Then detuning has little effect on the impedance at the sideband frequencies and the Robinson stability criterion may not be satisfied.

Fortunately a mechanism for self-limiting of the dipole oscillation may be discerned in the Bessel function representation of phase modulation. In particular, the amplitude term for the fundamental RF component of beam current is given by $J_0(\theta_p)$, which has a value of 1 at $\theta_p = 0$ and decreases toward zero at $\theta_p \cong 2.4$ radians. But this is the very component that drives the Robinson instability. As phase oscillation grows, the amplitude of this driving term decreases, providing negative feedback. However, the RF bucket limits $|\theta_p|$ to $<\pi/2$, so the effective range of $J_0(\theta_p)$ is limited to $0.472 < J_0(\theta_p) \leq 1$.

If this were the dominant stabilizing effect, one might expect steady-state dipole oscillation. This may be the situation observed near threshold. At increasing phase deviation the nonlinear restoring force gives rise to distortion of the bunch shape and growth of higher bunch modes. Frequency shifts and energy spread introduce Landau damping which tends to further limit the growth of oscillations. Then growth may be reversed and coherence may be lost, producing the relaxation oscillation described in this report.

Conclusion

The preceding discussion is based on the simple model of sinusoidal phase modulation of harmonically related carriers. This model assumes a rigid bunch shape and a linear restoring force, which clearly is not the case in real life. Depending on the balance among the Robinson, self-limiting feedback, nonlinear and Landau damping effects, the beam may be stable, show steady state oscillation, or exhibit relaxation oscillations. Further analysis by beam dynamics theorists is cordially invited.

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