High Intensity Bunch Length Instabilities in the SLC Damping Rings*

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I. INTRODUCTION

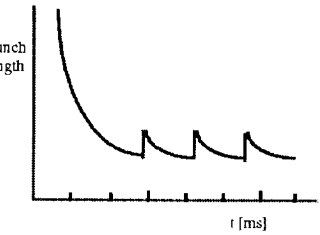
The SLC damping rings function to provide low emittance, short bunches for injection into the linac. As the beam intensity in the rings was raised, as part of the SLC luminosity improvement program[1], we observed a threshold above which beam jitter would occur in the linac. Frequent machine trips, caused by beam loss on some bunches, were associated with the jitter. These erratic "flier" pulses were traced to extraction phase errors from the damping rings. This paper covers the diagnosis of this condition and the observations of the transient bunch length instability phenomena. The evidence of this turbulent (microwave) bunch length instability is seen in both time domain and in frequency domain measurements. The instability has been dubbed the "sawtooth" because of the characteristic time dependent nature of the phase and bunch length signals. It is present in both the SLC electron and positron damping rings at about the same threshold of $3 \cdot 10^{10}$ particles per bunch.

An interim solution to this instability problem has been to exercise control over the bunch length via the RF voltage. The peak current is kept below the instability threshold by ramping the voltage during the store cycle. The blowup in the bunch length as the threshold of peak current (=intensity÷bunch length) is crossed, is the result of short-range wake fields. The main contributors to the vacuum chamber impedance are step discontinuities in transition pieces, radiation masks and pump slots. We are at present building a new, smoother vacuum chamber to reduce the impedance and thus increase the intensity in the damping rings.

Earlier measurements of bunch lengthening[2] in the damping rings led us to believe that the lengthening was an equilibrium process. It was the tight tolerance on the phase of the extracted beam that signaled to us the transient behavior of the bunch lengthening. Such tight tolerances on beam phase do not occur in storage rings and so the transient behavior is less important, although there is some evidence that "sawteeth" have been observed elsewhere[3]. There is also some evidence in numerical simulations of transient bunch lengthening phenomena, which is discussed later in this paper.

II. INSTABILITY OBSERVATIONS

The time dependent nature of the bunch length during the 8.3 ms store time in the damping ring is shown diagramatically in fig. 1. The bunch length decreases rapidly after injection, with a longitudinal damping time of the order of 2 ms. When the bunch length passes below a threshold a sudden blowup in bunch length occurs in a time span comparable to the 10 μs synchrotron period. The process is self limiting because of the nonlinear nature of the short range wake fields responsible for blowing up the bunch. Once the blowup ceases the bunch damps down until the threshold is reached again, causing a cyclical repetition of the instability. The time dependent nature is seen in the following two signals.



Bunch length signal

This is derived from the sum signal of a pair of Beam Position Monitor (BPM) electrodes. Passage of the bunch gives a bipolar pulse whose height is proportional to intensity÷bunch length. This signal is peak sampled-and-held at the revolution frequency of 8.5 MHz. The sampled output connected through a low pass filter to an oscilloscope gives a real-time display of the inverse of the bunch length during the beam store time. An example is shown in fig. 2.

Bunch phase signal

The behavior of the beam phase is important since it has direct bearing on how the bunch is launched into the linac. The bunch phase can be referenced to either the 714 MHz RF of the damping ring or to the 2856 MHz S-band RF of the linac. The 714 MHz beam phase shown in fig. 2 also exhibits sawtooth-like jumps at the same time that the bunch length signal blows up. The synchronous beam phase angle is given by $\phi_s = \sin^{-1} U_{loss}/V_{rf}$ so the changing phase during an instability reflects a changing energy loss per turn of the bunches. The higher order mode losses of the bunch are a function of the line charge density and so are inversely proportional to bunch length. As the bunch blows up the higher order mode losses decrease and the beam phase shifts. We observe an approximately 0.5° phase shift at 714 MHz during a sawtooth, which implies that at the nominal operating conditions of V_{rf}=1 MV and ϕ_s=9°, the energy loss per turn changes by 9 kV. This is to be compared to the 80 kV radiation losses and the nominally 80 kV higher order mode losses.

The 0.5° phase jump at 714 MHz translates into a 2° jump at S-band in the linac. This magnitude of phase error causes a problem with the RF bunch length compressor in the Ring To Linac beam line. A phase error at extraction transforms to an energy error in the compressor, resulting in both orbit and chromatic errors.

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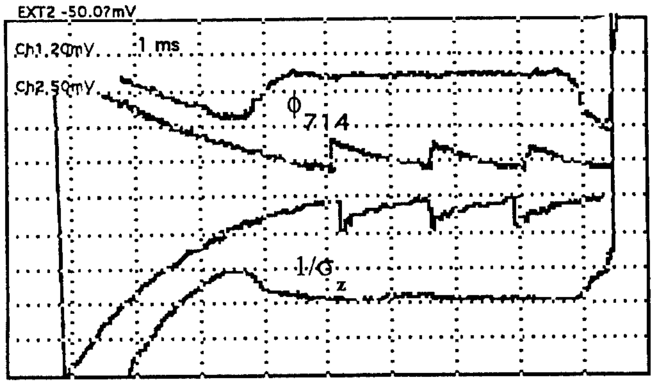


Fig. 2. The inverse bunch length signal and the beam phase signal exhibit sawtooth behavior during the instability. Upper and lower curves (no sawteeth) are with voltage ramp on.

The troublesome feature of the sawtooth behavior is that the timing of the phase hiccups will jiggle around and occasionally occur just at extraction. When this occurs the bunch will be incorrectly launched into the linac and may eventually be lost on the downstream collimators, causing the linac to trip the machine protection circuits.

The beam phase in the damping ring is controlled by an S-band beam-phase feedback loop. The gain-bandwidth of this loop rolls over well below the synchrotron frequency so it is unable to compensate for the rapid phase jumps of the sawtooth. The error signal for the S-band loop shows a series of spikes coincident with the onset of the sawtooth.

Frequency domain measurements

Turbulent bunch lengthening is often referred to as the microwave instability because the bunch length oscillation modes have a characteristic wavelength at some small fraction of the bunch length. For the short (<1 cm) bunch lengths in the damping rings this translates to frequencies in the 100 GHz range, well beyond the reach of our conventional RF measurement equipment. With some care in the setup we have been able to detect useful signatures of the instability at frequencies of up to 20 GHz.

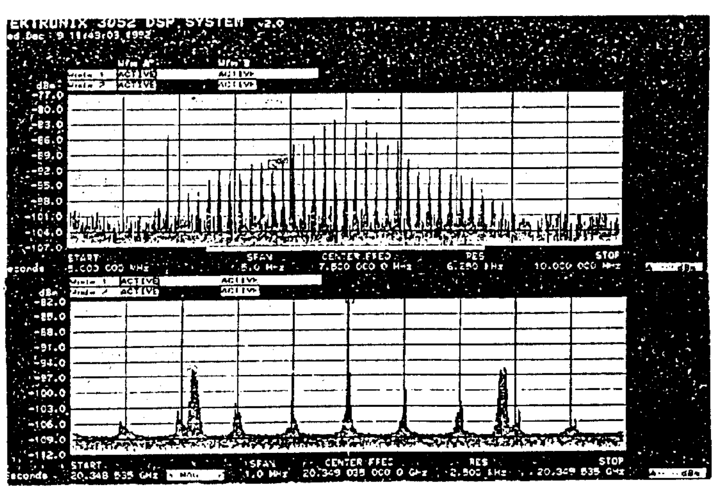


Fig. 3. a. At a harmonic near 20 GHz many modes are visible in the injected beam. (5 MHz span)
b. In the damped beam, with instability, the sextupole mode dominates. (1 MHz span)

The bunch evolves rapidly during the store time so the emphasis of our measurements has been on separating the frequency spectrum of the turbulent bunch lengthening from the spectrum generated by the bunch at injection. The application of a Digital Signal Processing spectrum analyzer has proven very useful here[4].

When the bunch is injected in the damping ring there is a considerable longitudinal mismatch. The bunch oscillates with many modes as seen by the large number of synchrotron sidebands in fig. 3a. If the spectrum acquisition is triggered later in the store cycle the modes are seen to have damped out. However, if the spectrum acquisition is triggered to occur after the bunch length has damped down to the instability threshold we see a strong signal reappear at the $3\nu_s$ sideband, corresponding to a sextupole mode of oscillation in the bunch length, fig. 3b. Note that although we refer to this sideband as $3\nu_s$ its frequency of ~260 kHz is considerably depressed from 3 times ν_s=100 kHz.

If spectral measurements are done on a stored beam (i.e. by disabling the extraction kicker) the behavior can be recorded as the intensity decays down to the threshold where the instability ceases. The observed behavior is that the $3\nu_s$ line is present during the whole time that the beam is unstable in the damping ring and disappears as soon as the instability stops. Significantly, we observed only a small frequency shift of the $3\nu_s$ mode with changing current (~8.6 kHz/$1{\cdot}10^{10}$). The other weaker modes, up to $6\nu_s$, exhibit similar frequency dependence. We had anticipated an intensity dependence of the mode frequency so that we could account for the instability in terms of longitudinal mode coupling, a phenomena observed at other storage rings[5,6]. An example of mode coupling would have been if the $3\nu_s$ sextupole line had crossed the $2\nu_s$ quadrupole line, but this did not occur.

Since we determined that the instability has its largest observable spectral component at $3\nu_s$, we set up a spectrum analyzer with zero span at this frequency and swept the time span from injection through to extraction. There is an initial large peak in the signal power corresponding to injection transients and then nothing until a sawtooth occurs at which point there is a brief rise in the spectral power. This confirms that the mode is only present during the brief instant that the bunch blows up. The question that is not resolved by these measurements is whether the mode is a symptom or the cause of the instability. It is conceivable that the very rapid bunch blowup is a turbulent process at very high frequencies within the bunch and that when it extinguishes, the mismatch of the bunch length within the RF bucket causes ringing, predominantly at $3\nu_s$.

III. INTENSITY DEPENDENCE

The threshold for the instability occurs at around $3{\cdot}10^{10}$ particles per bunch for a nominal RF voltage of 1 MV. At higher intensities we observe that the periodicity of the instability increases, i.e. the sawteeth appear closer together in time. The process can be viewed as a relaxation oscillator where the period is a function of the bunch length damping time and the trigger threshold. The damping time is constant but the bunch length at which the bunch goes unstable increases at higher intensities. As the intensity is increased the sawteeth get closer together until a transition occurs at around $4 \cdot 10^{10}$ to a second regime with "continuous sawteeth". The bunch-length and beam-phase signals have noise-like character in this regime. We do not observe that the bunch length ever reaches a quiet, steady state equilibrium between the heating and damping mechanisms.

The thresholds for these regimes also depends on the RF voltage as the equilibrium bunch length is $\propto V^{-1/2}$. At lower RF voltages the bunch takes longer to reach the instability threshold, so the frequency of the sawteeth is reduced. We describe later how to exploit this to avoid the instability altogether.

Bunch lengthening in the damping rings has been the subject of earlier studies[2]. At this time the onset of bunch lengthening was measured by measuring the energy spread of the extracted beam in a high dispersion beam line, as a function of current. Prior to making an impedance reduction in the vacuum chamber by sleeving the bellows, the bunch lengthening threshold was measured at $1.5 \cdot 10^{10}$. The measurement has been repeated since the sleeving was done and the new threshold is close to $3 \cdot 10^{10}$, fig. 4, coincident with the threshold for the sawtooth. The measurement of energy spread is performed over many machine pulses, masking any transient effects related to the sawtooth. Numerical simulations were able to predict the factor 2 improvement in the instability threshold from sleeving the bellows, but remained pessimistic about the absolute threshold value by approximately 30%.

The intensity distribution functions for bunch lengthening have been numerically simulated in several instances. In one example an undershoot phenomena[7] has been seen where the bunch damps below the instability threshold resulting in a sudden blowup. Unlike our sawtooth, these blowups rapidly damp after injection. A simulation of the LEP ring[8] has also shown periodic blowups of bunch length, but on a scale much larger than has ever been observed. A recent simulation with our damping ring parameters[9] has shown evidence of the strong sextupole mode above the threshold, but without any indication of a sawtooth behavior.

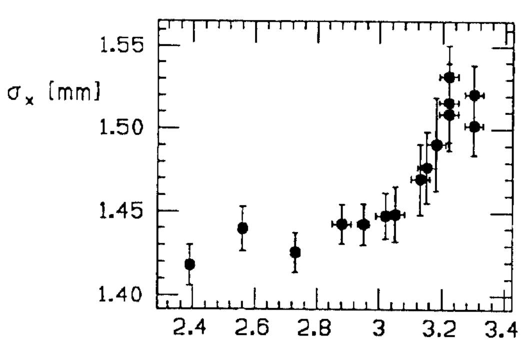
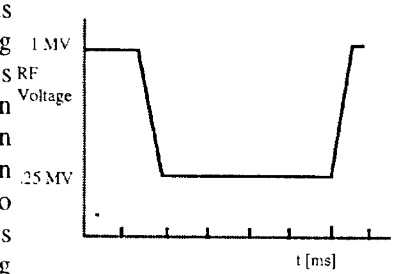


Fig. 4. The energy spread, indicated by the beam size in a dispersive region, shows the onset of turbulent lengthening at 3•10^10.

IV. Bunch Length Control Through the RF

Lowering the RF voltage is a means of increasing the equilibrium bunch length and extending the intensity threshold for the instability. A low RF voltage is not suitable for efficient injection where a large RF bucket is required. A low RF voltage is also unsuitable at extraction, since a very long bunch length at extraction results in an unacceptable energy spread in the compressor, causing the problems alluded to earlier, of beam loss and chromatic errors.

A solution has been implemented for ramping the voltage down approximately 1 ms after injection and ramping it back up around 0.5 ms before extraction as shown in the adjacent fig. 5. In this scheme the injection transients have time to decay but the voltage is soon reduced, preventing the bunch from damping below the instability threshold. The voltage is ramped up at the end of the store cycle so that the bunch shortens and it is extracted just before it has the chance to go unstable. The programmed voltage changes are made adiabatically so that the bunch remains matched to the RF bucket. A second voltage program (not shown) is used to shorten the bunch further by bunch rotation just before extraction[10]. Lowering of the RF voltage for both these manipulations has severe impact on the beam loading of the RF cavities. The short time scale of the ramp means the cavities can not be retuned for optimal matching at the lower voltage. This combined with the lower cavity power relative to the beam power leads to a beam loading instability at lower voltages. The beam loading has been succesfully compensated through the use of RF feedback[11]. We have been able to routinely suppress the onset of instabilities at intensities up to $3.5 \cdot 10^{10}$ per bunch by ramping the voltage from 1MV down to 250 kV during the beam store time.



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