SAW-TOOTH INSTABILITY STUDIES IN THE STANFORD LINEAR COLLIDER DAMPING RINGS †

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Abstract

Experimental results of the instability studies are being reported. The system built gives a BPM-derived single bunch 'instability signal'. The signal was recorded simultaneously with the longitudinal density bunch profiles obtained from the synchrotron light with the high resolution Hamamatsu streak camera. Correlation of the instability signal with the streak camera profiles has been found. For the strongly developed instability state the dominant mode structure was obtained.

1 INTRODUCTION

It's been reported earlier [1] that the installation of new SLC damping ring vacuum chambers eliminated the saw-tooth instability as a major obstacle for increasing the collider performance. However, the instability didn't go away as it was predicted by simulations. On the contrary, the threshold went down from 3×10^{10} to $1.5\text{-}2\times10^{10}$ particles per bunch. The new instability has a similar limiting behavior, but it apparently limits itself at a much lower level and doesn't affect the shape (and transport properties) of the extracted bunch as severely as the old one.

Here is a brief summary of the new instability properties from [1]. The instability is longitudinal and has a clear threshold behavior. It occurs with either one or two bunches in the ring suggesting a single bunch phenomenon. The presence of instability can be detected by a wire scanner in a dispersive region of the extraction line. It shows a rapid growth of the energy spread as a function of the bunch current above the threshold. More detailed information can be obtained with a spectrum analyzer connected to a beam position monitor (BPM) electrode. It detects the instability sidebands of high frequency revolution harmonics. The sidebands are about f_{inst}~180kHz apart from the rotation harmonics which is almost twice the (low current) synchrotron frequency f_{s0}=100kHz. That suggests that the instability has a predominantly quadrupole mode. The time evolution of the instability can be studied using the spectrum analyzer as a receiver set to a sideband frequency. It shows a different behavior for different current and/or RF voltage settings. The typical pattern is that the instability signal exponentially rises out of noise a few ms after injection and then oscillates in amplitude by 10-20dB with rise and fall times in the 250-500μs range which is comparable with the longitudinal damping time of ~1.9ms [2].The phase of the oscillations appears random with respect to injection.

Those studies did not give *quantitative* answers to important questions such as

- What is the phase space structure of unstable bunches?
- What is the instability effect on the subsequent acceleration in the linac?
- What is the physics of instability?

For the experiment reported here we concentrated on the first question. However, the hardware we developed also provided a tool to investigate the second. As for the last question, several instability mechanisms have been proposed [5-9]. But the referenced papers do not make quantitative predictions, and it is unclear which, if any, applies to our rings. We believe this paper will give more experimental input to address this important question.

2 SETUP AND HARDWARE

2.1 Experimental setup

As it was mentioned in [1] the instability properties in both electron and positron damping rings were similar. Due to some technical reasons the latter was chosen for the present experiment. The ring parameters can be found in [2]. There are two bunches circulating exactly opposite to each other during normal SLC operation. Each bunch is stored for 16ms before extraction, and the next bunch is injected in the middle of the store of the previous one.

There were two major beam diagnostic channels. Synchrotron light was analyzed by the streak camera, while

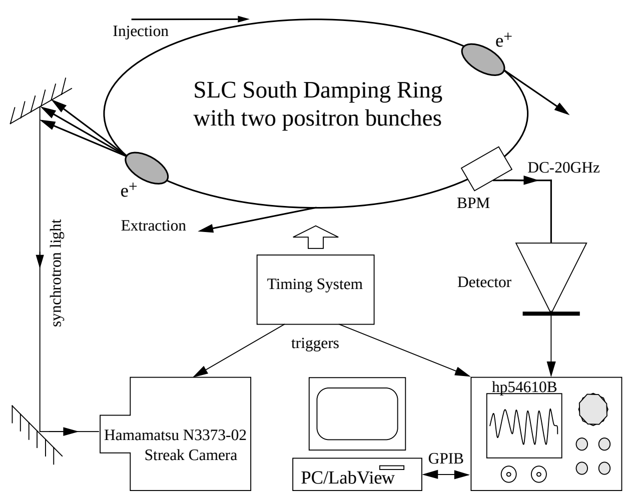

Figure 1. Experimental setup

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the high frequency BPM signal was processed and digitized by an oscilloscope. The key part of the experiment was simultaneous data acquisition; hence the timing was important. Both the camera and the scope were triggered on the same trigger pulse (locked to the injection cycle) provided by the SLC timing system. The streak camera profiles were recorded by its own computer while the scope traces were saved on a PC connected via GPIB bus.

2.2 Streak camera

The main device in the setup is the Hamamatsu N3373-02 streak camera with a cooled CCD head. This camera proved to be extremely valuable to study static beam properties [2]. However, mapping the dynamic bunch behavior after the onset of instability is a challenge due to some limitations of the camera. The main one is the slow acquisition speed of a few frames per minute. This prohibits taking multiple pictures within one store not to mention the instability period. One way to make sense from the profiles taken during different stores is to use an external 'instability signal' that measures the instability state when each profile is taken. The second major element in the setup, the BPM signal detector, provides that reference.

2.3 Detector

Instability phase space information is contained in the sidebands of the revolution harmonics [3]. Macroscopic phase space structure with symmetry m (m=1 for dipole, m=2 for quadrupole, etc.) creates sidebands at $nf_{rev}\pm mf_s$, n=0,1,... Measuring the radial phase space structure requires a calibrated, wideband pickup, but phase space orientation can be measured by the phase of any single sideband which could be determined after downmixing.

To observe significant instability amplitude one has to work at a relatively high frequency $f\sim m/2\pi\sigma$ where σ is the bunch length. For our bunch length f>10GHz is required. Squaring a pickup signal gives i) a DC term, dominated by the sum of the squares of the amplitudes of the rotation harmonics, ii) a signal at the instability frequency, f_{inst}, that arises from products of the rotation harmonics with signals at frequencies $nf_{rev}\pm f_{inst}$, and iii) higher frequency products. The second of these is the one of interest. It has considerably improved signal to noise as compared to downmixing a single instability sideband.

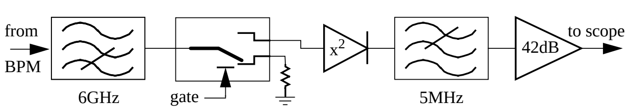

Figure 2. Detector schematic

The detector (Fig. 2) consists of a front end 6GHz high-pass filter to cut the overall power which is dominated by lower frequencies. The next element is a fast SPDT RF switch (with one output port normally termi-

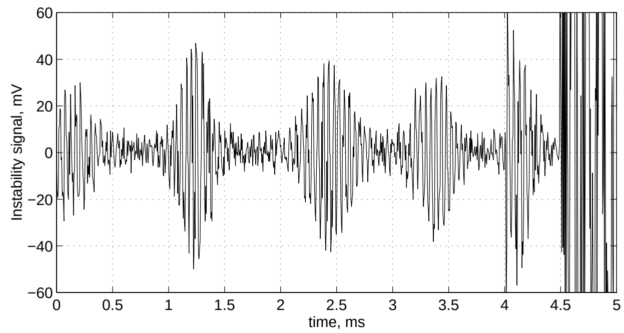

Figure 3. Instability signal after the detector

nated) gated at f_{rev}=8.5MHz. Gate delay and width were adjusted to pass the signal only from the bunch the streak camera was looking at. The next element is a square law crystal detector followed by a 5MHz low-pass filter which cuts higher frequency products. The resulting signal is fed into an audio amplifier (about 42dB gain at f_{inst}, 0 at DC) with the output connected to an oscilloscope.

A typical signal is shown on Fig. 3. Extraction occurs at t=4.5ms, and the spike at 4ms is caused by external modulation of the RF voltage [4]. We can clearly see the instability growing and damping in bursts of about 1ms feature size. The higher frequency component of these bursts is, in fact, f_{inst}.

This detector has a number of applications beyond the experiment reported in this paper. First, the signal from the bunch that is about to be extracted can be correlated with the downstream bunch behavior. It was measured that the instability could be one of the most significant jitter sources for SLC [4]. Second, the detector allowed us to study the cross-talk between the two bunches in the ring correlating the signals coming from two ports of the switch [to be published].

3 DATA TAKING AND PROCESSING

The experiment consisted of repeatedly taking the streak camera profile and simultaneously recording the detector signal. The scope time range was 100µs/screen - enough to cover about 20 instability periods. Both the camera and the scope were triggered on the same timing pulse always coming ~0.5ms before extraction and before any external modulation. The scope trigger position was adjusted so that the streak camera picture was shot exactly in the middle of the trace (Fig. 4). A total of 589 profiles were taken in the time-frame of several days under roughly the same running conditions.

The individual streak camera profiles didn't require processing other than a calibration [2]. Bringing all the profiles to the common time reference was less obvious, since the centroid position information was lost due to substantial (>30ps) trigger jitter. Whether there is any dipole motion of the bunch can be directly checked with a spectrum analyzer. The instability never causes measurable sidebands near f_s, so all the movements of the profiles

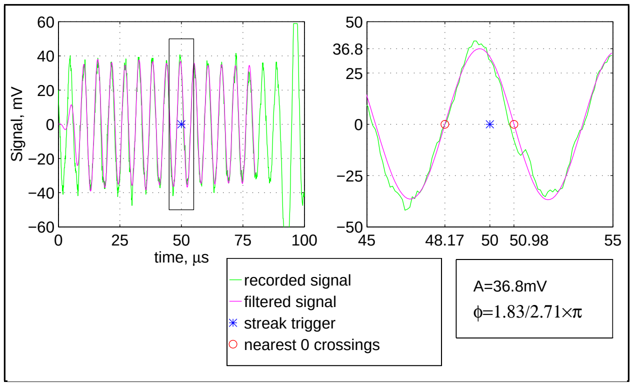

Figure 4. Extracting the instability phase and amplitude from the detector signal

on the streak camera screen were caused by trigger imperfections.This allowed us to find the zero dipole moment time point for each profile and assign t=0 to it.

The instability amplitude and phase at the moment of the streak camera shot were obtained from the scope traces (Fig. 4). To eliminate extraction related effects the last 20% of each trace was discarded and the rest was digitally filtered to reduce the noise (filtering details aren't important). We defined the phase of instability based on zero crossings of the filtered signal. For the amplitude we picked the maximum deviation of that signal in the 20µs region centered at the shot moment. Of course, the phase makes sense only when the amplitude is large, i.e. a burst and the shot coincide.

4 MAIN RESULTS

We ended up with a few hundred streak camera profiles each tagged with the instability amplitude and phase obtained from the scope traces. To study large amplitudes we selected the profiles with the instability amplitude between 20 and 40mV. Those 295 profiles were binned according to their phases. The average shapes for the $+\pi/2\pm\pi/4$ and $-\pi/2\pm\pi/4$ phase bins, and the overall average profile are shown in Fig. 5. The main changes as the phase

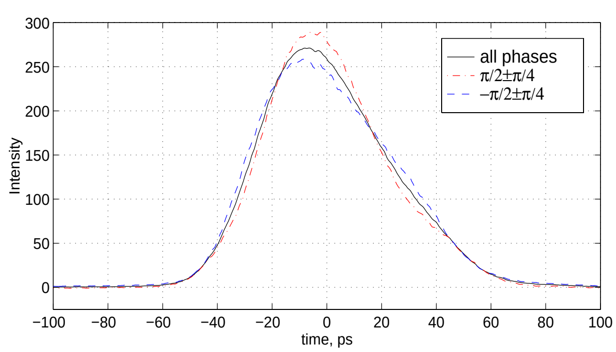

Figure 5. High instability amplitude case: average profiles for different instability phases

varies happen near the top as well as about 30ps into the head and into the tail. We found that the profile height at those regions varied in a sine-like fashion versus instability phase. Since this is a manifestation of the phase space rotation we defined the instability structure as $\delta\rho(\tau_i) = \langle(\rho_k(\tau_i) - \rho_0(\tau_i))/\sin\phi_k\rangle_k$, where ρ_k are all the profiles with corresponding phases ϕ_k, k=1,2,...295, ρ_0 is the phase-averaged profile (Fig. 5, solid) and angle brackets denote the median value.

The structure obtained is plotted on Fig. 6. It is very much like a projection of a quadruple mode (sketched in the corner). The ratio of the positive peak area to the one under ρ_0 is about 3% which measures the amount of redistributed particles creating the quadrupole structure.

For the low amplitude case we found the average profile, and it is similar to ρ_0 for high amplitudes. That means that the difference between the beam distributions when the instability is high or low is less than our sensitivity and the characteristic feature size on Fig. 6.

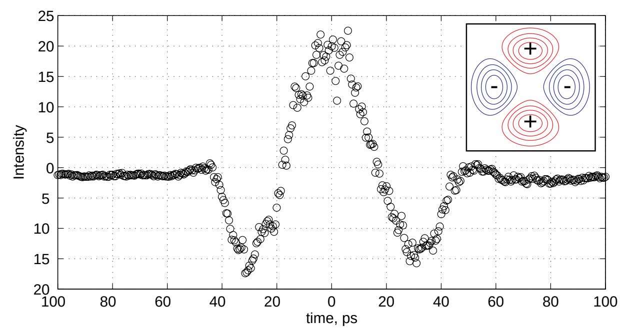

Figure 6. High amplitude instability structure

5 SUMMARY AND CONCLUSIONS

We have built a BPM signal processing circuit that proved to be valuable for single bunch longitudinal diagnostics in a multibunch environment. Combining that detector with the streak camera we have measured the phase space features for the strongly developed saw-tooth instability. The instability is predominantly quadrupole and contains approximately 3% of the beam. In addition, the average profile at large instability amplitudes is the same as the distribution at small amplitude. These facts make it likely that the instability can be interpreted with perturbation techniques.

We plan to continue our instability studies with upgraded hardware and with theoretical work.

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