Head-Tail Damping Measurements at SRC*

Ian Hsu** and Walter Trzeciak
Synchrotron Radiation Center, University of Wisconsin, Madison, WI 53589, USA

Abstract

The head-tail damping rate at injection energy (108 MeV) in Aladdin was measured for different beam currents. At this low energy, the beam may suffer strong Landau damping due to the trapped ion. A profile monitor was implemented to conform that the beam is damped down coherently. The profile monitor signal agree with the simulation results and the damping rate agree with the theory prediction.

1 Introduction

Aladdin is a 1 GeV electron storage ring located at the Synchrotron Radiation Center of the University of Wisconsin, Madison. It has been in operation as a synchrotron radiation source since 1985 with average accelerated currents of about 200 mA.[1] It had been suspected that the Head-tail damping mechanism is one of the reason for the anomalous fast stacking rate which let Aladdin be able to accumulate more than 200 mA.[2] It is understood that , whether the beam will head-tail damp or not, is dependent on the competition of the Landau damping effect[3] and the ability of the beam to perform a coherent motion. The reason for that is because that the head-tail damping (or instability) is a coherent damping (or instability) and the Landau damping has the effect of preventing the beam from assembling a coherent motion.

The injection energy of Aladdin is 108 MeV. That means that at the injection energy, it suffers a very severe ion trapping problem[4], which in turn provides a very strong Landau damping effect. So, even though, the theory clearly predicts that there will be head-tail damping when we operate the machine at positive chromaticity, it is really necessary to do an experimental study. The head-tail damping has been observed in SPEAR[5], but compared to the case which we are interested in here, that is both a high energy and a high current case.

2 The calculation of the damping rate

To completely describe the head-tail instability or damping, we use the superposition of a complete set of orthonormal functions to describe the beam motion[6]. Each function represents a mode of motion. In the case in which we are interested, the injected beam executes a dipole mode, so we only consider the dipole mode in the following discussion.

The general result of the head-tail damping rate was derived by Sacherer[6]. Setting the mode number m equal to zero (dipole mode), we have

$$Damping\ rate = \frac{eI}{2\sigma_l E\omega_\beta}\sum_{p=-\infty}^{p=\infty} Re\{Z_\perp[(p+\nu_x)\omega_0]\}h_0[(p+\nu_x)\omega_0-\omega_\xi] \quad (1)$$

where I is the bunch current, σ_l is the bunch length, E is the beam energy, ω_β is the angular betatron oscillation frequency, ω_0 is the angular revolution frequency, $\omega_\xi \equiv \frac{\nu_x\omega_0\xi}{\alpha}$ is called the chromaticity frequency, $Re[Z_\perp]$ is the real part of the transverse impedance, and h_0 is the zero order Hermite function with the normalization $\sum_{p=-\infty}^{p=\infty} h_0(p\omega_0) = 1$.

The transverse broad band impedance of Aladdin is calculated from the measured value of $\frac{Z_\parallel}{n} = 17\ \Omega$[7] by the following formula[8] :

$$Z_\perp(\omega) = \frac{2R}{b^2}\frac{Z_\parallel/n(\omega_r/\omega)}{1+i[(\omega/\omega_r)-(\omega_r/\omega)]} \quad (2)$$

where R is the average radius of the storage ring (circumference/2π), b is the typical vacuum pipe radius, and ω_r is the resonance frequency of the vacuum pipe. Figure 1 shows the real part and the imaginary part of the broad band transverse impedance of Aladdin.

When comparing the measured result with the theory, we can use Equation 1 and ask the computer to do the summation to the term where either the impedance goes to zero or $h_0(\omega)$ goes to zero. We can also use the long bunch length and small chromaticity approximation. In the case which we are studying in Aladdin that is a very good approximation. Under this approximation, the impedance in the frequency range of interest can be linearized. After replacing the summation by an integration and after some manipulations, we get a nice simple formula :

$$Damping\ rate = \frac{c^2 eIZ_{\perp 0}\xi}{2\sigma_l E\omega_r\alpha} \quad (3)$$

where $Z_{\perp 0}$ is the real part of the transverse impedance at the resonant frequency and α is the momentum compaction. From Equation 3 we can see that the damping rate is proportional to the beam current, $Z_{\perp 0}$, and the chromaticity, and is

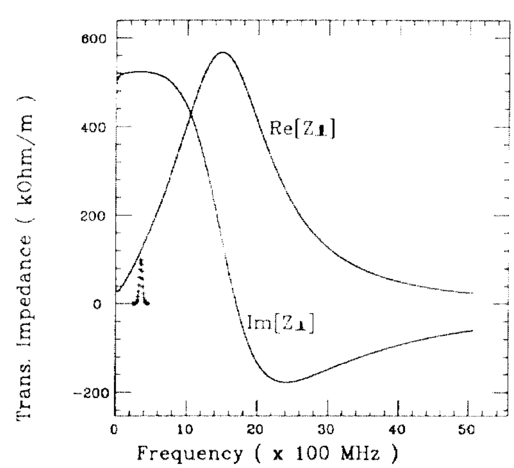

Figure 1: The broad band transverse impedance of Aladdin. The '+' curve is the spectrum of h_0 which is a gaussian distribution and the central frequency is the chromaticity frequency ω_ξ. In this figure, ω_ξ = 0.356 GHz, ξ = 0.5.

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**Current address : SLAC, Bin 66, P.O. Box 4349, Stanford, CA 94309, supported by DOE through SLAC.

inversely proportional to the beam energy and bunch length. From Fig. 1, we see that the linear dependence of the chromaticity in Equation 3 is true only for the small chromaticity approximation. Figure 2 shows the chromaticity dependence of the damping rate which is calculated from Equation 1 by performing the summation without any approximation. We can see that the good linear dependence is up to chromaticity 2.

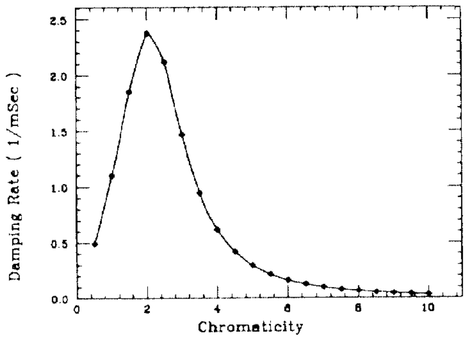

Figure 2: The chromaticity dependence of the damping rate obtained by performing the summation in Equation 1 for the parameters of Aladdin. In this plot the bunch current is 2.3 mA and the bunch length is 1.5 meters.

3 Experimental set up

The measurements were made on the Aladdin storage ring running at injection energy 108 MeV and in a single bunch mode which was made by using the RF knockout frequency to knock out the unwanted 14 bunches. One of the injector kickers is used to kick the stored beam. After the kick dies out, the beam will execute a coherent free betatron oscillation. A single 50 Ω terminated beam position monitor electrode is connected to a pulse stretcher. It is necessary to lengthen the 2 ns bunch length to about 100 ns for the purpose of digitizing the signal. A Data Precision 6000, which can digitize a signal in 10 ns, is used to digitize and store the beam position on every revolution for 10,000 turns. The instrument is triggered right before we fire the kicker and clocked by the ring master oscillator. The data is then transferred to a VAX 750 for analysis.

The signal received from a beam position pickup is proportional to the displacement of the center of charge (or mass) of the whole bunch of electrons. If instead of coherent damping, the beam is decoherent, we will get a reduced amplitude beam position signal. Therefore, to distinguish whether the beam is coherently damping down or is decoherent, we need a beam profile monitor. The synchrotron radiation emitted by the beam at a bending magnet and an optical system is used for that purpose. The optical system includes a pin hole, a pipe, an adjustable slit and, a photon multiplier tube (PM tube) followed by a pre-amplifier. The synchrotron radiation signal from the PM tube is then fed into a Tektronix 7834 Storage Oscilloscope which is also triggered right before we fire the kicker. Figure 3 is a schematic drawing of the set up for measurement of the head-tail damping rate.

4 Data treatment

The data picked up from the beam position monitor electrode contains all sorts of noise. If we calculate the damping rate by the result of a direct beam position signal amplitude measurement, the noise will make the error bar of the damping

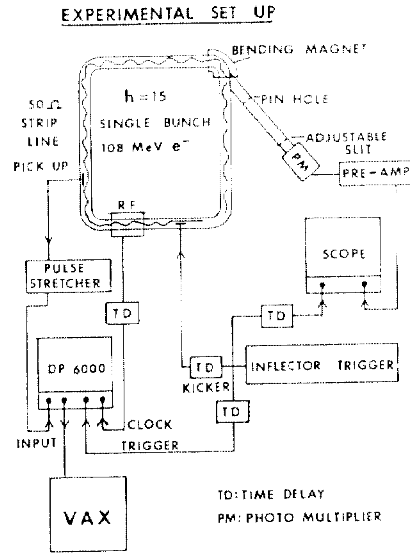

Figure 3: A schematic drawing of the experimental set up for the head-tail damping rate measurement.

rate become very large. This kind of measurement is the so called time domain measurement. Figure 4 is one of the typical data in the time domain. To improve that, we do this measurement in the frequency domain. This was done by the software. A program was written to read the data in the time domain and divide the data into some smaller segments, e.g. each segment contains 500 data points, then do a FFT of each segment. The program then determines the amplitude of the frequency in which we are interested i.e. the betatron oscillation frequency. The damping rate was got by knowing the change of amplitude. By using the software to do this measurement in the frequency domain, the accuracy has at least been improved by a factor of 5.

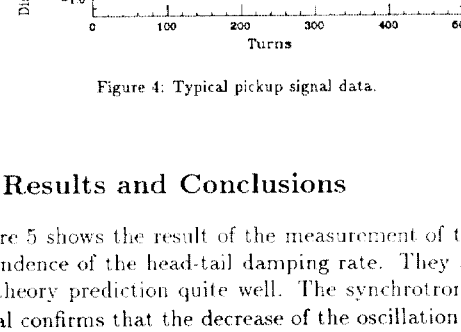

Figure 4: Typical pickup signal data.

5 Results and Conclusions

Figure 5 shows the result of the measurement of the current dependence of the head-tail damping rate. They agree with the theory prediction quite well. The synchrotron radiation signal confirms that the decrease of the oscillation amplitude of the beam position signal is really coherent damping, not decoherent. Figure 6 is the pictures taken from the storage scope and Fig. 7 is the plots of a simulation result for the synchrotron radiation signal. The top picture and plot are the results for the coherent damping. The bottom ones are the results for decoherence. The signal coming out from the

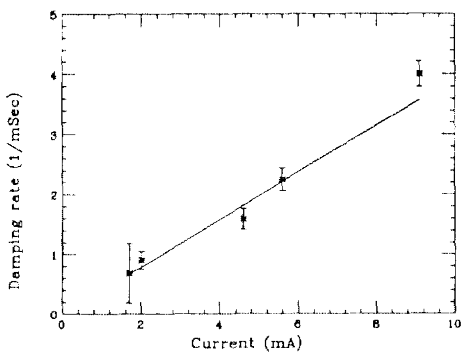

Figure 5: The measurement of the current dependence of the damping rate. The line is predicted by the theory.

PM tube is a negative signal. Before we kick the beam, all of the synchrotron radiation goes through the pin hole and the slit. That is why there is a big signal (like a spike) at the beginning. After we kick the beam, if the beam is executing a coherent betatron oscillation and the oscillation amplitude is damping down, because the signal showing up on the storage scope is actually an average over a time of some betatron oscillations, the signal will begin to increase. (Due to the negative signal of the PM tube, it gets more negative.) On the other hand, if the beam decoheres after we give a large kick, the beam smear and the beam size become very large. Only a small part of the total synchrotron radiation can go through the pin hole and the slit, thus, the signal stays small and does not increase.

The measured damping rate agree well with the theory for the current above 1.7 mA. However, when the beam current goes below 0.8 mA we can no longer see the coherent damping behavior from the PM tube signal. (The bottom picture in Fig. 6 is the case for I = 0.65 mA.) It seems that the Landau damping effect is too strong to let the beam at this current level perform coherent motion. Seeking for some more evidence for this, we changed the chromaticity to a negative value. At 0.8 mA beam current, we did not see any instability. This again conform that at 0.8 mA beam current the Landau damping effect is stronger than head- tail coherent motion.

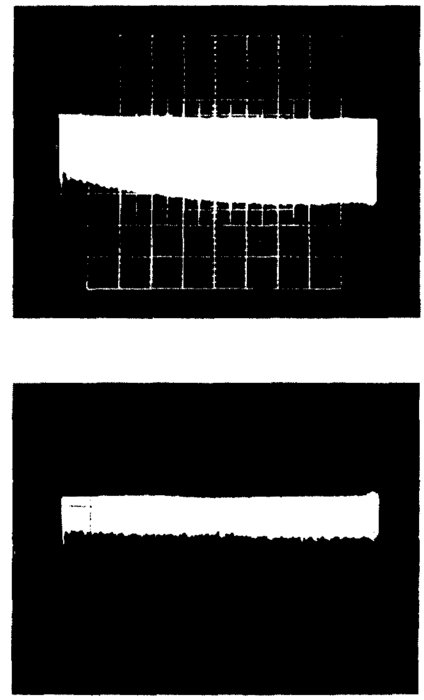

Figure 6: The pictures taken from the scope of the synchrotron radiation signal. The top picture is the result for coherent damping. The current is 1.81 mA. The bottom one is the result for decoherence. The current is 0.65 mA. The horizontal scale is 2 msec/div

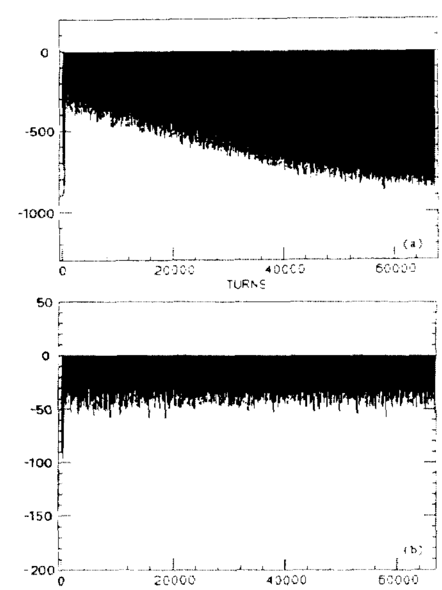

Figure 7: The plots of a simulation result for the synchrotron radiation signal. The top plot is the result for coherent damping. The bottom one is the result for decoherence. To produce the decoherent effect, we add an octupole magnet to the lattice which was used to produce the top result.

6 Ackonwledgment

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