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Longitudinal Beam-Transfer-Function Measurements at the SLC Damping Rings*

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LONGITUDINAL BEAM-TRANSFER-FUNCTION MEASUREMENTS AT THE SLC DAMPING RINGS *

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Abstract

A longitudinal single-bunch instability [1] in the damping rings at the Stanford Linear Collider (SLC) is thought to contribute to pulse-to-pulse orbit variations in downstream accelerator sections. To better understand this instability, we measured the beam phase and bunch length under harmonic modulations of the rf phase and rf voltage. For small phase-modulations the measured response can be explained by interaction of the beam with the cavity fundamental mode. For larger excitations, we observed bifurcation and hysteresis effects. The response to an rf voltage modulation revealed two peaks near the quadrupole-mode frequency, one of which appears to be related to the longitudinal instability. In this paper we present the experimental results.

1 INTRODUCTION

Beam-transfer functions measurements (BTFs) were first suggested [2] as a technique by which to determine beam stability limits and the coupling impedance of the beam environment. Since then, measurements have revealed a rich spectrum of beam physics. For example, ring impedance studies were carried out using coasting beams by at the ISR in 1977 [3], and for bunched beams at SPEAR in 1990 [4]. In 1992, Byrd performed a comprehensive study of collective phenomena in CESR [5]. More recent measurements from the IUCF [6] have used BTF's in the study of nonlinear effects including the creation of resonance islands, beam splitting, chaos and bifurcations.

parameter	symbol	value
circumference	C	35.27 m
momentum compaction	α	0.015
beam energy	E	1.19 GeV
rf frequency	f_{rf}	714 MHz
harmonic number	h	84
rf gap voltage	V_c	800–860 kV
synchrotron frequency	f_s	$\sim$ 100 kHz
long. rad. damping time [7]	τ_{rad}	1.55 ms
rms bunch length	σ_z	5.3–6.8 mm
relative energy spread	σ_δ	9×10^{-4}
bunch population	N_b	0–2.6$\times10^{10}$
number of klystrons/cavities	N_k/N_c	1/2

Table 1: Damping ring parameters during measurement.

We here describe experimental studies at the SLC damping rings in which we externally modulated the phase or amplitude of the RF cavities. Typically, the beam was injected and stored, with the modulation turned on. The response was measured using a network analyzer (50 s sweep time, 1 kHz rbw, 401 discrete frequency steps). The parameters of the SLC Damping Rings are shown in Table 1. All measurements were performed with a single bunch.

2 PHASE MODULATION

Ignoring Landau damping, the synchrotron motion of the beam centroid is described by the same type of differential equation as the single-particle motion [8]. Representing an rf phase modulation as a harmonic perturbation, including the Robinson interaction, and linearizing the rf potential, the equation of motion is

$$\ddot{\psi} + 2\lambda\dot{\psi} + \omega_s^2\psi = \hat{\phi}\,\nu_m^2 e^{j\omega t}, \quad (1)$$

where ψ is the relative phase of the beam with respect to the modulated RF phase (which, at low current, equals the beam phase w.r.t. the cavity voltage); i.e.

$$\psi \equiv \phi - \hat{\phi}\sin(\nu_m\theta + \chi), \quad (2)$$

In Eq. (1), $\lambda = 1/\tau$ is the Robinson damping rate, ω_s the angular synchrotron frequency, $\hat{\phi}$ the modulation amplitude, $\nu_m f_{rev}$ the modulation frequency, χ a constant phase factor, and for simplicity the synchronous phase angle has been set to zero. Defining[1] the complex beam transfer function BTF as the ratio of the beam centroid phase and the rf modulation amplitude $\hat{\phi}$,

$$\mathrm{BTF}(\omega_m) \equiv \frac{\bar{\phi}(\omega_m)}{\hat{\phi}}, \quad (3)$$

the amplitude of the BTF is a Lorentzian

$$A_{\mathrm{BTF}}(\omega_m) = \omega_m^2\left(\frac{1}{(\omega_s^2-\omega_m^2)^2 + 4\lambda^2\omega_m^2}\right)^{1/2} \quad (4)$$

and its phase is

$$\theta_{\mathrm{BTF}}(\omega_m) = \tan^{-1}(-\lambda/(\omega_s-\omega_m)). \quad (5)$$

Shown in Fig. 1 is a BTF measured in the positron damping ring (SDR) for a small phase-modulation depth ($\hat{\phi} \approx 0.006°$) and low beam current ($N_b \approx 7\times10^9$). The data were acquired by modulating the phase of the 714 MHz drive using a network analyzer which output an excitation of fixed amplitude and variable (swept) frequency to a fast phase shifter located upstream of a klystron. The

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[1] Note that this definition differs from that in Refs. ([4, 5], which both define the BTF as $\dot{\bar{\phi}}/(\hat{\phi}\omega_m^2)$.

phase of the beam with respect to the cavities was measured using a detector which mixed the signals from a cavity pickup and from a single stripline of a beam position monitor. The detector output was normalized to the modulation output. Figure 1 demonstrates that the measured response is well described by Eqs. (4) and (5) with a damping time $1/\lambda$ equal to the measured (coherent) oscillation decay time of ~ 3500 turns.

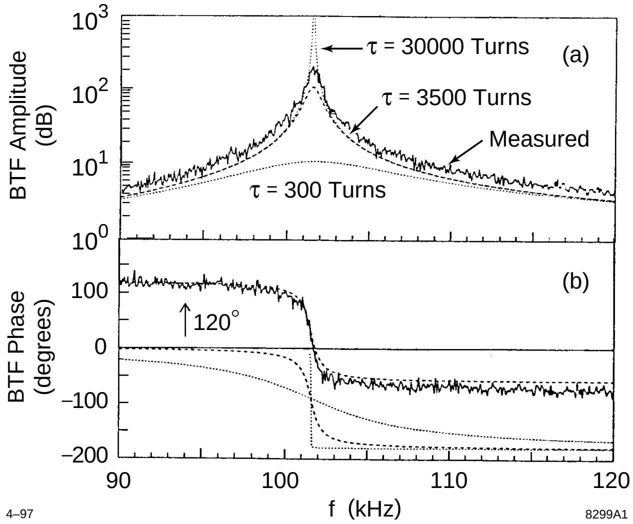

Figure 1: Comparison of measured BTF amplitude and phase with Eqs. (4) and (5) for a single-bunch population $N_b \approx 7 \times 10^9$ and small excitation, $\phi_{rms} \approx 0.004°$.

We also calculated the beam phase response that would be expected from Landau damping due to the nonlinearity of the RF voltage, in this case ignoring the Robinson damping. The calculated response agreed poorly with measurement which indicates that the single-bunch measurement was dominated by the Robinson interaction.

Figure 2 illustrates the dependence of the BTF on the excitation amplitude. For low excitation amplitudes the response is Lorentzian as in Fig. 1. With increasing modulation depth the response revealed an asymmetric behavior, characteristic of a driven nonlinear oscillator. In particular, a pronounced dip transition was observed at frequencies somewhat below the peak-response frequency.

An oscillatory solution of the nonlinear equation of motion (*i.e.*, for a sinusoidal rf potential) is [9] $\psi(\theta) = \alpha \sin(\nu_m \theta)$. The fixed-point amplitude α is approximately described by a cubic equation, which bifurcates at a modulation frequency $f_m = f_{rev}\nu'_m$:

$$\frac{\Delta\nu}{\nu_s} \equiv \frac{\nu_s - \nu'_m}{\nu_s} = \hat{\phi}^{2/3} \left(\frac{3}{8} 2^{1/3}\right), \qquad (6)$$

At the bifurcation point, one of two stable fixed points vanishes. In Eq. (6), f_{rev} is the revolution frequency and $\nu_s \equiv \omega_s/(2\pi f_{rev})$ the synchrotron tune. Fitting a straight line to the measured data of $\log \Delta\nu/\nu_s$ versus $\log \hat{\phi}$, we find a slope of 0.637 ± 0.015 and an intercept of -0.875 ± 0.08. This is consistent with the expected slope ($\frac{2}{3}$) and intercept (-0.76) from Eq. (6), which supports the assertion that the

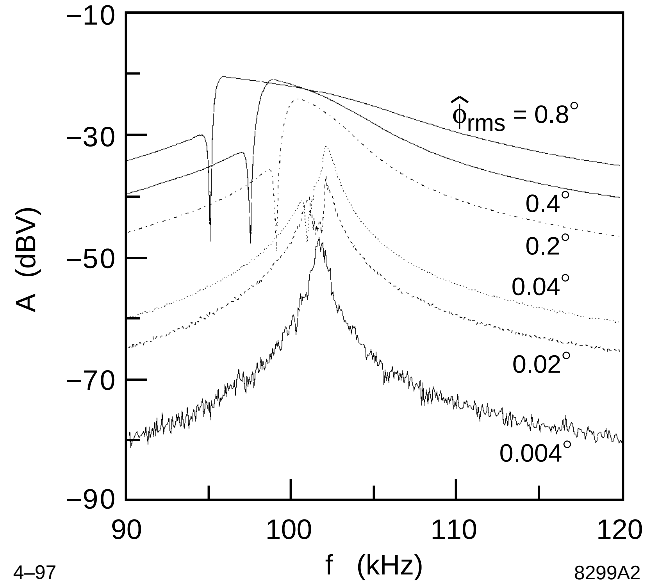

Figure 2: SDR beam-phase transfer function for various excitation amplitudes. The single-bunch population is about $N_b \approx 3$–7×10^9.

dip is related to a transition between the two fixed points. The origin of the dip has been studied in more detail recently at the ALS [10].

Because the beam response is strongly reminiscent of a driven nonlinear oscillator, we expect to see a different response curve when the frequency is swept downward. This is demonstrated in Fig. 3, which shows two beam-phase transfer functions for up- and downward frequency sweeps. At large excitation, we observe a clear hysteresis effect.

3 VOLTAGE MODULATION

Shown in Fig. 4 is the measured response of the beam peak current to an rf amplitude modulation in the SDR. The data were acquired by modulating the amplitude of the 714 MHz drive using an rf attenutator. The detected peak current signal is inversely proportional to the bunch length. As illustrated in Fig. 4, the response curve for the SDR revealed two peaks. In contrast, only a single peak was detected in the electron damping ring (NDR). Fig. 5 summarizes the current dependence of the response peaks in the two damping rings. The lower-frequency peak in the SDR and the peak in the NDR show a current-dependent frequency similar to that predicted for the longitudinal instability (7 kHz/10^{10} [11]). The higher-frequency peak of the SDR occurs almost exactly at $2\nu_s$. In the SDR, the beam response to a voltage modulation was largest when the two response peaks came close to each other. This happened both for large excitations ($\Delta V/V \geq 3\%$) and for low bunch intensities ($N_b \leq 10^{10}$). The peculiar shape of the phase response (bottom part of Fig. 4) may contain additional information about the instability.

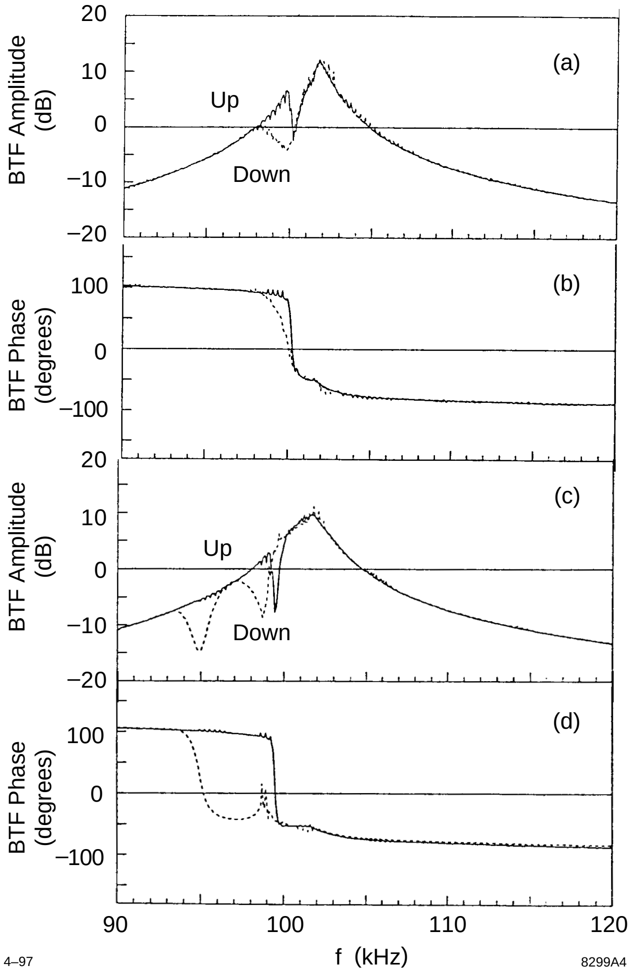

Figure 3: Comparison of SDR beam-phase transfer functions for upward and downward frequency sweeps at different excitation amplitudes.

4 OUTLOOK

The reasonably good agreement between the measured beam response and Eq. (4) suggests that, at low current and for low excitation, the response is dominated by the Robinson interaction with the fundamental cavity mode. It is difficult therefore to extract information about the beam distribution and/or the broad-band impedance. A more direct approach would be to excite an $l \neq 0$ multi-bunch mode [5], since this would suppress the effect of the fundamental mode. A measurement of the broadband impedance may improve our understanding of the longitudinal instability, and resolve the discrepancy between the inductive impedance calculated with MAFIA and that required to reproduce the observed instability in simulations [11].

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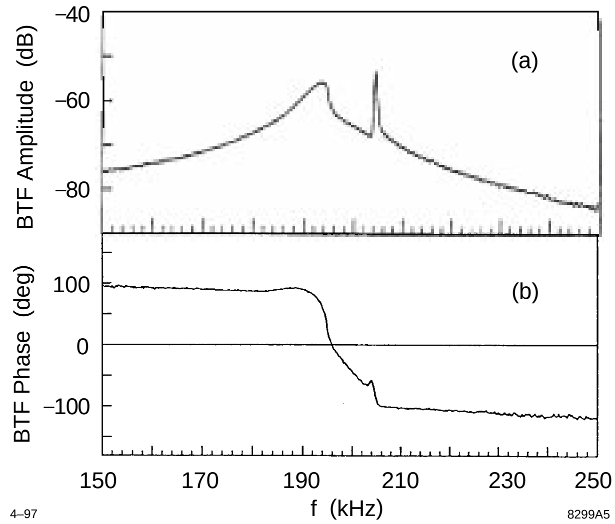

Figure 4: Voltage-modulation BTF in the SDR with $N_b = 1.6 \times 10^{10}$ and an rms gap voltage modulation of 2 kV.

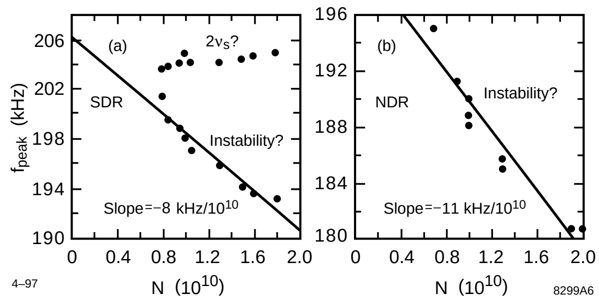

Figure 5: Peak response function of voltage-modulation BTF as a function of current.

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