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Transverse beam stability measurement and analysis for the SNS accumulator ring

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ABSTRACT

A field-programmable gate array (FPGA)-based transverse feedback damper system was implemented in the Spallation Neutron Source (SNS) accumulator ring with the intention to stabilize the electron–proton (e–p) instability in the frequency range of 1–300 MHz. The transverse feedback damper could also be used as a diagnostic tool by measuring the beam transfer function (BTF). An analysis of the BTF measurements provides the stability diagram for the production beam at SNS. This paper describes the feedback damper system and its setup as the BTF diagnostic tool. Experimental BTF results are presented and beam stability is analyzed by use of the BTF measurements for the SNS accumulator ring.

1. Introduction

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory is a high-intensity neutron-scattering research facility. The facility uses a 1 GeV proton beam on a spallation target. For this use, SNS delivers 24 μC pulses, which are 695 ns long, at a 60 Hz repetition rate to a spallation target. There are upgrade plans to bring the beam power of the SNS accelerator to 2 MW [1]. Interactions between electrons and the proton beam in the ring may produce an electron–proton (e–p) instability. In 2006, Danilov et al. [2] observed an e–p instability with its peak at 78 MHz at 2×10^{13} proton particles for a high intensity coasting beam with zero chromaticity. In 2008, a series of dedicated high intensity experiments [3] were performed to create an e–p instability on the bunched beam by varying the first harmonic RF cavity. Observations demonstrated that an e–p instability was established with peak frequencies in 60–80 MHz band beginning at the 550th turn of beam accumulation in the vertical plane and the 650th turn in the horizontal plane [3]. In 2011, Cousineau reported that the location of the instability within the beam bunch, the plane in which it occurs, and the threshold intensity of the e–p instability at SNS all vary on a case-by-case basis [4]. In the 2012 Accelerator Advisory Committee Close-out Report[1] for the Spallation Neutron Source, it was reported: “There have been some studies of instability dependencies on various machine parameters, but recently there have been few studies at higher currents where these instabilities are likely to be a problem.” As SNS continues to increase the beam intensity, the e–p instability is believed to have the potential to increase beam loss and ultimately limit the amount of power that can be delivered to the target.

Beam feedback dampers have been used effectively to control instabilities in various high-intensity proton accumulator rings [5–9]. The transverse feedback damper system [10–12] for the accumulator ring at the SNS was developed to stabilize the production beam for potential e–p instability. The feedback damper system consists of two independent transverse feedback dampers, a horizontal and a vertical. Both feedback dampers are band limited between 1 and 300 MHz.

Feedback damper systems have demonstrated their capability as powerful beam diagnostic tools by measuring the beam transfer function (BTF) at several high intensity accumulator rings [13–15]. With this technique, the transverse BTF measurement provides direct measurement of the machine impedance, fractional betatron tune, and the beam stability diagram. However, few studies have been conducted on applying the BTF measurement and connecting the measurements to stability diagram theory. Chou et al. [13] showed some results of vertical BTF measurements in the Fermilab main ring. Eddy et al. [14] demonstrated that the stability diagram for the Fermilab Recycler ring might indicate some stability shift caused by its machine impedance. Paret et al. [15] showed an effective method for examining the dependence of space charge effects on beam intensity by measuring the stability diagrams acquired at a heavy ion synchrotron.

This paper presents the stability diagram theory and connects the analysis and theory with BTF measurements. In the BTF measurements,

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efforts have been made to account for de-embedding effects caused by electrodes, digital/analog circuitry, amplifiers, and beam current from the S-parameter transmission measurements. Experimental results show that this technique is particularly useful for measuring the beam stability for transverse modes within the system bandwidth.

2. Description of the transverse feedback damper system at SNS

There are two transverse feedback dampers in the transverse planes at SNS. Fig. 1 shows a general block diagram of the damper. Each damper consists of a beam pickup electrode, a mixed-signal electronic system, power amplifiers, and a beam kicker electrode. The electronic system consists of an RF hybrid, low-level RF (LLRF) circuitry, an FPGA-based digital signal processor, and two 400 W Eltac/InterTronic® RA961 power amplifiers [16] for driving the kicker. The system delay and gain are both flexible variables that can be digitally adjusted. The revolution harmonics are rejected by use of a comb filter designed on the FPGA. A digital FIR filter is implemented to compensate for dispersion caused by the cables and RF electronics. The system operates in a bandwidth between 1 and 300 MHz in each plane. For timing and diagnostic measurements, each damper is triggered and synchronized by the accelerator timing system.

3. Beam transfer function theory

The transverse equation of motion [17] for a single particle driven by a sinusoidal excitation $A\cdot e^{-j\omega t}$ and being subject to collective effects is given by

$$\frac{d^2y(t)}{dt^2}+\Omega_i^2\cdot y(t)=A\cdot e^{-j\omega t}+j\cdot\frac{eI_0\cdot\langle y\rangle}{\gamma m_0 L}\cdot Z_\perp \tag{1}$$

where y is the transverse beam displacement, $\langle y\rangle$ denotes the average transverse beam displacement, Ω_i is the betatron frequency of an individual particle, e and m_0 are the charge and mass of the charged particle, respectively, I_0 is the beam current, γ is the relativistic mass factor, L is the accelerator circumference, and $Z_\perp$ is the transverse impedance of the accelerator. Eq. (1) can be described as a feedback loop given by Fig. 2, where the outer loop is described by the driving term related to $Z_\perp$. Without loss of generality, additional feedback loops can be added for driving terms related to other instabilities or feedback dampers.

The BTF with zero accelerator impedance is given by [17,18]

$$B_0(\omega)=\frac{1}{2}\left[\pi\rho(\omega)+j\cdot\mathcal{P.V.}\left(\int_{-\infty}^{\infty}\frac{\rho(\Omega_i)}{\Omega_i-\omega}d\Omega_i\right)\right] \tag{2}$$

where $\mathcal{P.V.}$ stands for the principal value of the integral and ρ is the normalized distribution of the spread in betatron frequency Ω_i.

Assume that the average beam response is

$$\langle y\rangle(t)=y_1\cdot e^{-j\omega t}. \tag{3}$$

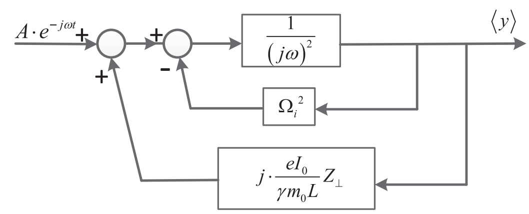

Fig. 2. Feedback loop for Eq. (1). The outer closed loop is the driving term related to the machine impedance $Z_\perp$. Without loss of generality, additional feedback loops can be added for driving terms related to other instabilities or feedback dampers.

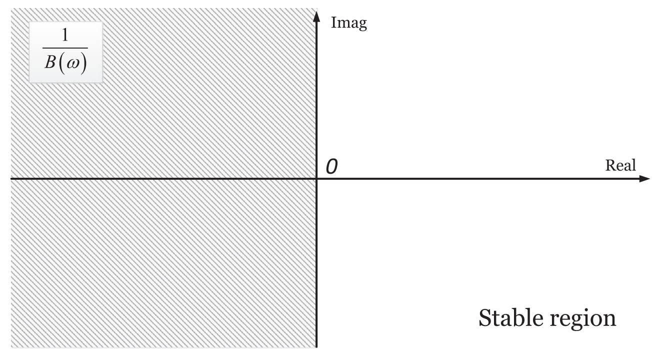

Fig. 3. The stability region obtained by plotting the inverse of the BTF on a complex plane. A beam is unstable when its stability diagram resides in the shaded area.

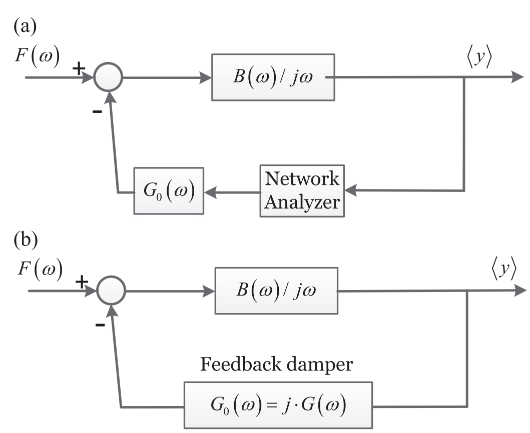

Fig. 4. Schematic of a beam with the feedback damper. Schematic of the beam with the feedback damper: (a) schematic of a beam with an open-loop measurement by using a network analyzer between the components of the feedback damper, (b) schematic of a beam with a closed-loop transverse damper.

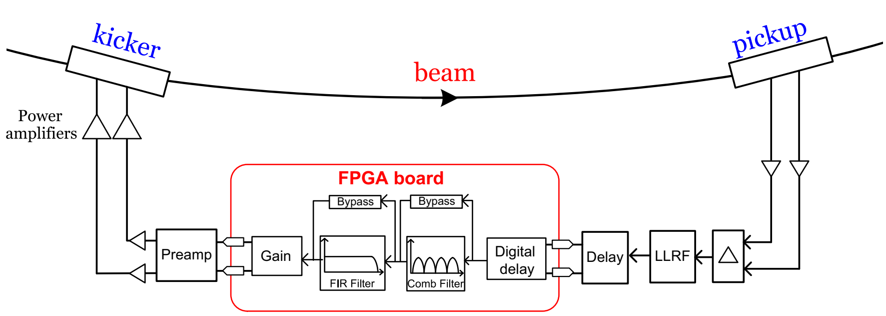

Fig. 1. Block diagram of the SNS transfer feedback damper.