DEVELOPMENT AND COMMISSIONING OF BUNCH-BY-BUNCH LONGITUDINAL FEEDBACK SYSTEM FOR DUKE STORAGE RING*

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Abstract

The coupled bunch mode instabilities (CBMIs) due to vacuum chamber impedance limit and degrade the performance of the storage ring based light sources. A bunch-by-bunch longitudinal feedback (LFB) system has been developed to stabilize the electron beam for the operation of a storage ring based free-electron laser (FEL) and the High Intensity Gamma-ray Source (HIγS) at the Duke storage ring. Employing a Giga-sample field-programmable gate array (FPGA) based processor (iGp), the LFB is capable of damping out the dipole mode oscillation for all 64 bunches in the Duke storage ring. As a critical subsystem of the LFB system, a kicker cavity is developed with a center frequency of 938 MHz, a wide bandwidth ($>$ 90 MHz), and a high shunt impedance ($>$ 1000 Ω). First commissioned in summer 2008, the LFB has been operated to stabilize high current multi-bunch operation. More recently, the LFB system is demonstrated as a critical instrument to ensure stable operation of the HIγS with a high intensity gamma beam above 20 MeV with a frequent top-off injection to compensate for the substantial and continuous electron beam loss in the Compton scattering process.

INTRODUCTION

The wakefield generated by beams interacting with discontinuous vacuum chambers can cause the coupled bunch mode instabilities (CBMIs) which limit the performance of the storage ring. Beam stabilization is crucial to improve the beam performance. Feedback systems are necessary to damp these harmful CBMIs. A time-domain bunch-by-bunch LFB system is used to damp longitudinal dipole CBMIs.

The LFB kicker is used to supply a proper correction energy to suppress the CBMIs. Several types of kicker were developed for the LFB system at different accelerator facilities such as a coaxial drift-tube kicker at ALS [1], a pill-box cavity with striplines at SRRC/TLS [2], and an waveguide over-loaded cavity at DAΦNE [3]. The DAΦNE kicker has a low Q-factor, a high shunt impedance, a high beam power capability, and a low higher-order mode (HOM) effect. This type of kicker has been used at KEKB, BESSY-II, PEP-II, SLS, and PLS [4].

The LFB signal processor system is the key component to process the beam signal. The old LFB signal processor systems were implemented using VXI/VME based digital signal processor (DSP) farms which are still working at PEP-II and PLS. The latest generation digital system is an integrated Gigasample processor (iGp) system which is based on the field-programmable gate array (FPGA) technology. The iGp system has a higher performance and broader bandwidth for data processing.

In 2007, a bunch-by-bunch longitudinal feedback system (LFB) was developed at the Duke storage ring. We have developed a 2-port LFB kicker based on the PLS kicker design [4] and use the iGp digital system [5]. The details of our LFB system are discussed in the following sections.

FEEDBACK KICKER DESIGN AND TEST

The LFB kicker provides a proper accelerating voltage to compensate the energy error of each circulating bunch. The Duke LFB kicker consists of a pill-box cavity, four overloaded waveguides, and a beam pipe [3]. The schematic of the kicker is shown in the Fig.1.

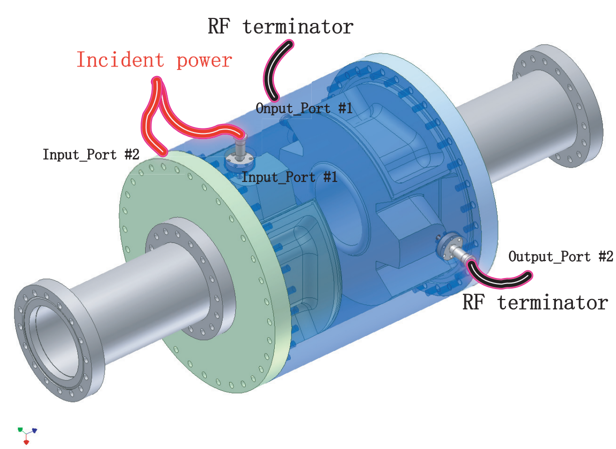

Figure 1: A 3D model of the Duke LFB kicker.

The kicker is driven by strong coupling waveguides attached to the pill-box cavity. Two input feedthroughs are connected to a power amplifier. Two output feedthroughs are connected to dummy loads. The beam-induced HOM power in the kicker is absorbed by RF terminators.

For M uniformly filled, evenly spaced circulating bunches in a storage ring, the frequencies of coupled bunch

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modes are described as [6]

$$f_{p,n,m} = \mid p \cdot M f_0 + n \cdot f_0 + m \cdot f_s \mid, -\infty < p < \infty, \quad (1)$$

where f_0 is the revolution frequency of the electron beam, p can be any integer, n is any integer between 0 and $(M - 1)$, m is the mode number associated with the longitudinal oscillation, and f_s is the synchrotron oscillation frequency. If M is the harmonic number of the RF cavity, the $f_{p,n,m}$ becomes

$$f_{p,n,m} = \mid p \cdot f_{\mathrm{RF}} + n \cdot f_0 + m \cdot f_s \mid, -\infty < p < \infty. \quad (2)$$

Since all the coupled mode frequencies $f_{p,n,m}$ are located within a sideband between $p \cdot f_{\mathrm{RF}}$ and $(p + 1/2) \cdot f_{\mathrm{RF}}$, the minimum BW of the kicker is $1/2 \cdot f_{\mathrm{RF}}$ and the center frequency of the kicker can be either $(p+0.25)f_{\mathrm{RF}}$ or $(p+0.75)f_{\mathrm{RF}}$.

In the PLS storage ring, four waveguide ports are used in the LFB kicker to obtain the 250 MHz bandwidth (BW) [4]. Since the Duke storage ring uses a RF system with a lower frequency of 178.6 MHz, the required BW of Duke kicker is about 90 MHz. Two waveguide ports are adequate to achieve the desired BW for the Duke LFB kicker.

To determine the kicker center frequency, the kicker efficiency needs to be considered. The Duke kicker was designed to work at 937.4 MHz, or 5.25 f_{RF} [7]. The expected quality factor $Q_l = 10.4$ where $Q_l = f_c/\mathrm{BW}$. The BW could be refined by modifying the parameters of waveguide ports and the gap of pill-box cavity.

The kicker performance determines the capability of the LFB system to supply the energy correction for each bunch. The kick gap voltage is proportional to the square root of the shunt impedance,

$$P_r = \frac{|V_{\mathrm{gap}}|^2}{2R_s}, \quad (3)$$

where P_r is the required RMS power supplied by the amplifier, V_{gap} is the kicker gap voltage, and R_s is the peak shunt impedance of the kicker. Therefore, a higher shunt impedance leads to more efficient CBMIs damping for a given input RF power. The internal pill-box cavity and coupling waveguides were optimized to achieve a higher shunt impedance. A nose-cone structure was introduced into our kicker cavity to increase the peak shunt impedance. Fig. 2 shows the simulated shunt impedance of the kicker with a peak value, 1570 Ω, at 938.0 MHz. Table 1. summarizes and compares the designed and simulated and/or measured kicker parameters.

In May 2008, we fished the kicker fabrication and testing. The kicker S-parameters were measured using a network analyzer. The RF power was coupled into the kicker from two upstream ports with the other two ports terminated.

The measured kicker center frequency is 15 MHz lower than the design value, a 1.5% decrease. The measured kicker BW is 3 MHz wider than the design value, a 5.5% increase. Since the LFB kicker is a low Q and a broad BW cavity, these discrepancies are not expected to significantly change the performance of LFB.

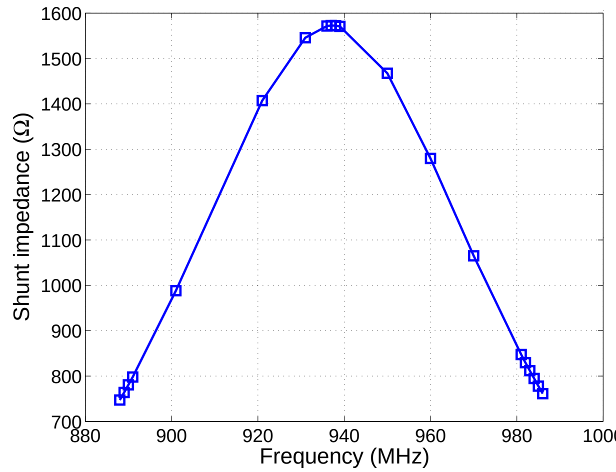

Figure 2: The simulated shunt impedance of the LFB kicker.

Table 1: Duke LFB kicker cavity parameters.

Parameter	Design	Simulated	Measured
Frequency (MHz)	937. 4	938.0	923.1
Bandwidth (MHz)	90	92	95
Shunt impedance (Ω)	1400	1570	
Quality factor	10.4	10.1	9.7
R_s/Q (Ω)	134.4	155.6	

DUKE LFB SYSTEM

The Duke LFB system is illustrated in Fig. 4. This LFB system consists of three subsystems: a phase error detection subsystem, a digital signal processing subsystem, and an energy correction subsystem. The phase error detection is achieved by a BPM signal pickup and front-end electronic unit. Four BPM buttons are combined to suppress transverse orbit sensitivity and the resulting signal is stretched by a 4-cycle comb generator with 700 ps tap spacing. The comb generator output is mixed with the 8th harmonic of the storage ring RF frequency, phased in quadrature with the beam. Therefore the front-end electronic unit can measure the arrival time of each bunch. The digital signal processing subsystem is implemented using an iGp processor. An FIR filter in the iGp system processes the phase error and calculates the energy correction value for each bunch. The energy correction subsystem is composed of a back-end electronic unit, a power amplifier, and a LFB kicker. The correction signal from the iGp is converted into an analog signal by the back-end electronic unit and sent to the power amplifier. Finally, the required energy compensation is supplied by the LFB kicker.

In June 2008, we began to commission the Duke LFB system. The LFB system suppressed all the CBMIs successfully. Fig. 5 shows a 64-bunch operation of the Duke

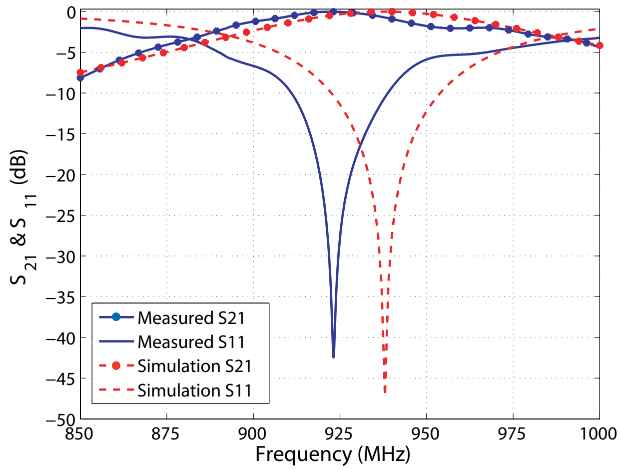

Figure 3: S-parameter comparison between experiment and simulation data.

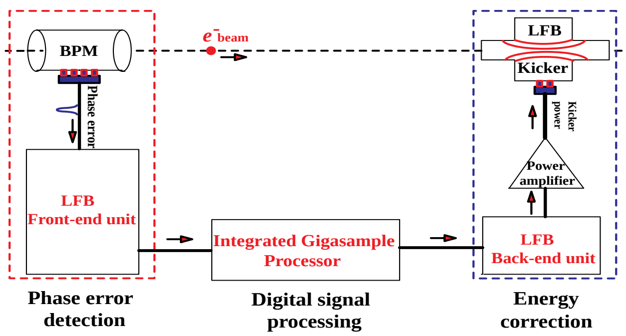

Figure 4: Schematic data path layout of the LFB system.

storage ring. The ring was operated at 574 MeV with a total store beam current of 50 mA. The synchrotron oscillation and its higher harmonic oscillations were excited (Fig. 5a) when the Duke LFB system was turned off. Fig. 5b shows the beam spectrum after the LFB was turned on. All the CBMIs were damped and the electron beam became stable. The LFB system has been used to stabilize the electron beam operation with various bunch-patterns, including the single-bunch beam and all evenly filled multi-bunch beams up to 64 bunches.

SUMMARY

In this paper, the kicker design and optimization is discussed. The development of the Duke LFB system is described. The measurement results show that we have achieved our goal with the LFB system. The LFB system has been successfully used to stabilize the electron beam for multi-bunch operation at the Duke storage ring. The LFB system has been found to be a critical instrument to ensure stable operation of a high electron beam current for Duke FELs [8] and the High Intensity Gamma-ray Source [9].”

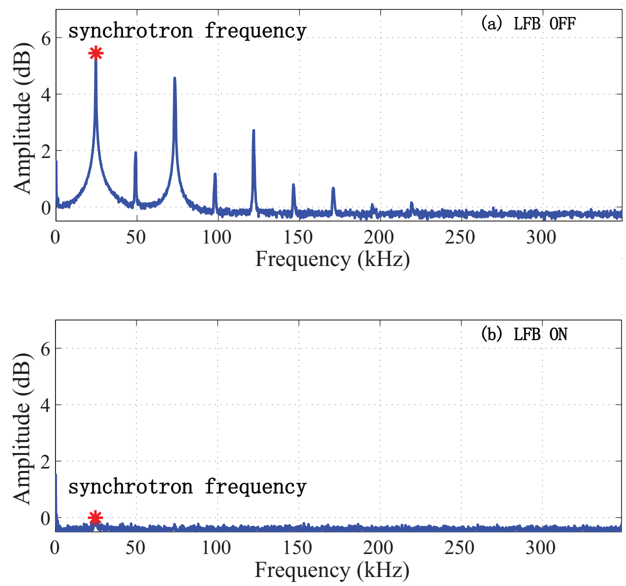

Figure 5: The 64-bunch beam operation at 574 MeV with a 50 mA beam current in the Duke storage ring. (a) LFB was off. (b) LFB was on.

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