MEASUREMENTS OF COUPLED-BUNCH INSTABILITIES IN BEPC-II

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Abstract

BEPC-II is a two ring electron-positron collider designed to operate at 1 A beam currents. Longitudinal and transverse coupled-bunch instabilities have been observed in both electron and positron rings. In this paper we present measurements of both transverse and longitudinal instabilities with the identification of active eigenmodes, measurements of growth and damping rates, as well as of the residual beam motion levels. The measurements will then be used to estimate the growth rates at the design beam currents (yet to be achieved). We will also demonstrate how such data is used for specifying power amplifier and kicker parameters.

INTRODUCTION

BEPC-II is a two ring electron-positron collider with high design beam currents. Main machine parameters are summarized in Table 1. In a collider it is critical to maintain beam stability in all planes to achieve design luminosity. In recent measurements, a loss of specific luminosity was observed along the bunch train [1]. Possible causes included electron cloud instabilities in the positron ring.

In order to investigate these effects a series of coupled-bunch instability measurements was performed. In this paper, we present the results of these measurements and, using offline models, calculate the required feedback kick voltages to reach the design beam currents.

Table 1: BEPC-II Parameters

Parameter	Value
Energy, GeV	1.89
RF frequency, MHz	499.8
Harmonic number	396
Beam current, mA	910
Number of bunches	93
Bunch spacing, ns	8

MEASUREMENT SETUP

Both transverse and longitudinal instability measurements used the same hardware, configured appropriately for each application. BPM-derived signal — vertical orbit error (Δy) for the transverse case and the sum signal for the longitudinal case — was processed and detected by the FBE-500L RF signal processor. The front-end section of the device is illustrated in Figure 1 and includes BPM signal processing for flat-top detection, adjustable RF gain features, and detection at 1.5 GHz. Detection is performed using a double-balanced mixer with the LO port driven by 1.5 GHz carrier locked to the ring RF. LO phase was adjusted for phase detection during longitudinal feedback experiments and for amplitude detection in transverse feedback mode.

Baseband output from the front-end was sampled by the iGp-396F bunch-by-bunch feedback processor at the RF frequency. The above device generates analog bunch-by-bunch kick signal after 16-tap FIR processing. iGp-396F integrates multiple data acquisition and beam diagnostic features which were used to perform the steady-state and the transient measurements.

Both transverse and longitudinal experiments used existing transverse feedback kicker, four diagonally-located 600 mm long striplines driven by four 75 W power amplifiers [2]. For the transverse feedback the output of the baseband processor was applied to a network of difference hybrids to generate proper stripline phasing. In the longitudinal feedback mode a four-way power splitter with matched cables was used to drive the power amplifiers in-phase.

BEAM MEASUREMENTS

Vertical Measurements

Initial studies were performed in the vertical plane of the positron ring. After single-bunch gain adjustments, timing, and phasing, the ring was filled to 90 mA with 50 bunches at 8 ns spacing. Large amplitude betatron motion was observed as well as its suppression after the feedback loop closure. Under these conditions we obtained several grow/damp measurements, one of which is illustrated in Fig. 2. Several eigenmodes are seen in these measurements with modes 28 and 32 being the dominant ones. A more precise determination of eigenmodes could be performed using an even fill pattern. In the above transient both modes show growth rates of 0.3 ms^{-1} with feedback damping of 1.2 ms^{-1}. In order to achieve maximum kicker voltage the feedback kick pulse was "stretched" from 2 to 8 ns. Achieving full kicker voltage with 2 ns long striplines requires at least a 4 ns drive pulse (2 ns fill time and 2 ns transit time). Using an 8 ns long pulse provides additional improvement due to finite DAC and amplifier rise times.

The unstable modes seen in this transient are most likely driven by an HOM impedance. Resistive wall would excite low-frequency modes, with the fastest growth rate for mode 99 (-1).

With the vertical feedback loop closed we observed significant longitudinal motion with oscillation amplitudes in-

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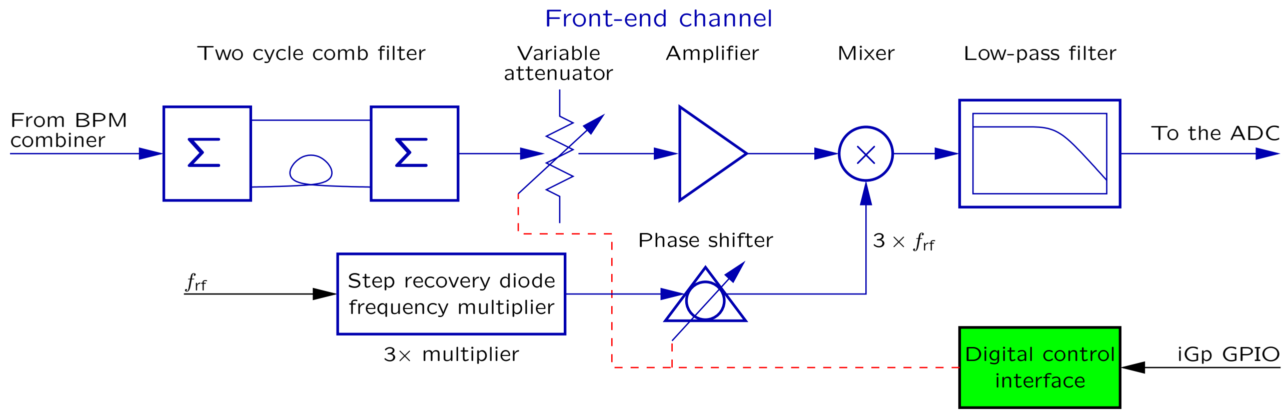

Figure 1: Block diagram of the front-end section of the FBE-500L RF signal processor.

creasing along the bunch train. Consequently, further studies concentrated on characterizing this motion.

Longitudinal Measurements

The first goal of longitudinal instability studies was to determine if the beam was actually unstable or driven by the RF system. A key indicator is the behavior of the beam once the longitudinal feedback loop is opened. Unstable oscillations show amplitude growth of $e^{\lambda t}$ with positive growth rate λ, while driven motion responds as $1 - e^{-\lambda_{\rm rad} t}$ where $\lambda_{\rm rad} = 1/\tau_{\rm rad}$ is the radiation damping rate.

Longitudinal kicker function of 2 ns long striplines has zeros at DC and 250 MHz with peak response at 125 MHz [3]. Consequently, baseband drive with 2 ns long pulses does not use such kicker efficiently. It is possible, however, to demonstrate feedback operation and to characterize the motion by keeping beam currents low.

Longitudinal feedback studies in the positron ring started with a single-bunch fill in order to optimize the front and back-end timing as well as RF front-end gain and carrier phase. Once these tasks were accomplished we were able to excite or damp the beam by applying positive or negative feedback as illustrated in Fig. 3 by the single-bunch spectra.

Having established feedback operation we injected a multibunch fill, increasing the current until large-amplitude oscillation was observed. Near the threshold current the feedback was able to suppress the motion and to produce the desired grow/damp measurements. One such measurement is shown in Fig. 4. Oscillations grow exponentially after the feedback loop is opened, leaving no doubt that the motion is due to coupled-bunch instabilities rather than external excitation. Even-fill eigenmode analysis shows three strong modes: 45, 51, and 93. Instability threshold is 70 mA in the even-fill pattern and shifts to 53 mA with the 50-bunch train fill typically used in BEPC-II.

Similar measurements in the electron ring showed higher instability threshold current of 172 mA and a different modal pattern: 7, 55, and 61. Mode 61 growth rates as a function of beam current are presented in Figure 5. From such measurements we can estimate the growth rate at the design beam current of 1 A as 0.62 ms^{-1}.

Longitudinal Feedback Kick Calculation

An important goal of the low-current instability measurements is to collect sufficient data to determine the necessary longitudinal kick voltage at the design operating conditions. Feedback configuration at a given beam current is determined by two elements: instability growth rates and external perturbations (RF noise, injection). A reasonable

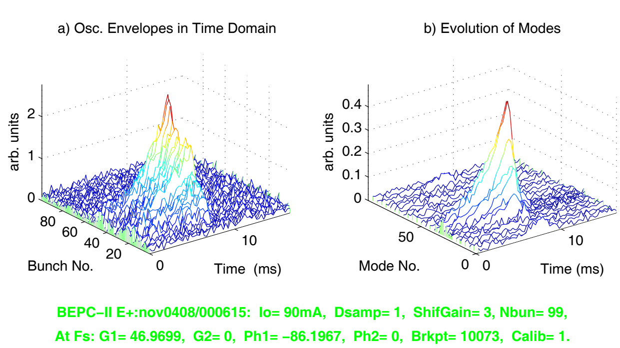

Figure 2: Vertical grow/damp measurement at 90 mA.

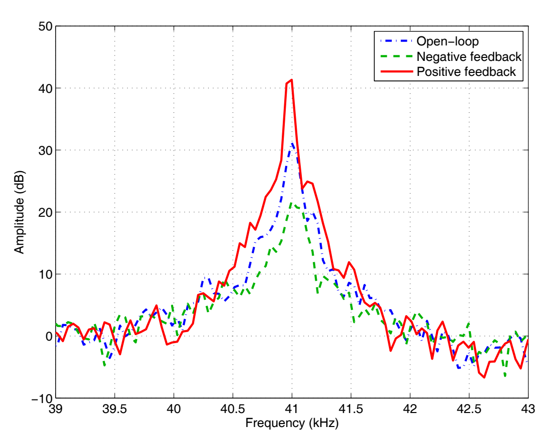

Figure 3: Positron ring longitudinal single-bunch spectra

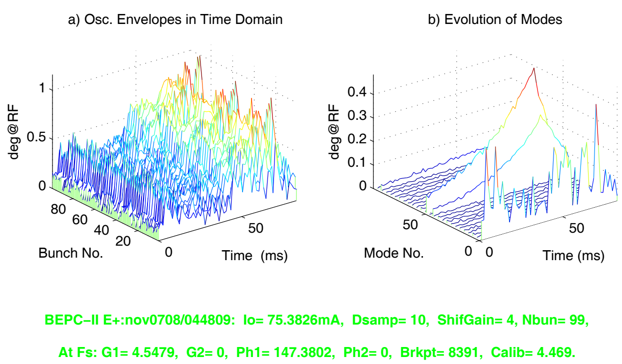

Figure 4: Grow/damp measurement in the positron ring showing three unstable modes: 45, 51, and 93. Noisy signal in the modal plot is the lowest frequency mode (mode 0) driven by the RF system.

rule of thumb for robust operation is to configure the feedback system so that the closed-loop damping rate is equal to the open-loop growth rate. That requirement sets the overall feedback gain at the synchrotron frequency $G_{\rm fb}$, as defined by Eq. 1 [4].

$$\lambda_{\rm fb} = \frac{1}{\tau_{\rm fb}} = \frac{2}{\tau_{\rm growth}} = \frac{f_{\rm rf}\alpha e}{2EQ_s}G_{\rm fb} \qquad (1)$$

Gain $G_{\rm fb}$ has to be partitioned between the front-end, digital signal processing, and the back-end. External disturbances set a limit to how high the front-end and the DSP gains can be due to the DAC output saturation. To determine the minimum necessary back-end gain these disturbances must be accurately modeled. Such modeling is done using an updated version of a time-domain model described in [5]. Several wideband and narrowband noise sources in the model are adjusted to replicate the closed-loop beam phase spectrum measured by the ADC at low beam currents. Next, we model the system at the full design current, using the growth rate estimated earlier. Gain partitioning in the model is then adjusted to achieve steady-state kick RMS of 60–70% of full-scale. Such modeling makes two

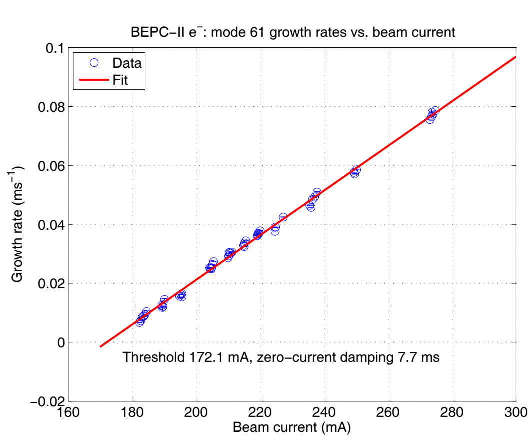

Figure 5: Mode 61 growth rates versus beam current

assumptions: a) noise sources do not change as a function of current; b) injection transients are not a significant source of perturbations.

Table 2: Kicker Parameters

Parameter	Positron ring		Electron ring	
	Base	Design	Base	Design
Beam current, mA	76	1000	205	1000
Growth rate, ms^{-1}	0.04	8	0.03	0.63
Damping rate, ms^{-1}	0.11	8.7	0.3	0.65
RMS kick, %FS	60	60	74	63
Digital gain at f_s	123	123	122	30.5
Kick voltage, V	9.4	147	20	62
Amplifier power, W	300	*27*	300	*5*
Shunt impedance, Ω	*0.15*	400	*0.67*	400

Table 2 shows the modeling results for both rings. For the base measurement effective kicker impedance was estimated assuming full 300 W drive power. The very low estimated impedance is partially explained by the sub-optimal baseband kick configuration, but also points to possible problems in the stripline kicker drive. For the design current estimate we assume a typical longitudinal kicker shunt impedance and compute the required amplifier power based on the model-defined kick voltage.

SUMMARY

A series of coupled-bunch instability measurements was performed at BEPC-II, starting with the vertical plane in the positron ring and then concentrating on characterization of newly identified longitudinal instabilities in both rings.

Longitudinal grow/damp and closed-loop measurements at low beam currents were used to parametrize Simulink models of BEPC-II longitudinal dynamics and feedback. Resulting models are critical for estimating the necessary kick voltages at the design beam currents. Detailed time-domain simulations allow to optimize gain partitioning, given the competing goals of minimum amplifier power, good damping margins, and external disturbance rejection.

REFERENCES

[1] C. Zhang, L. Ma, and J. Q. Wang, "Construction and commissioning of BEPCII," in *these proceedings*.

[2] J. Yue, L. Ma, J. Cao, and L. Wang, "Performance of the transverse coupled-bunch feedback system in the BEPCII storage ring," in *Proceedings of 40th ICFA ABDW 2008, Novosibirsk, Russia*, pp. 63–65, 2008.

[3] G. Lambertson, "Dynamic devices: Pickups and kickers," *AIP Conf. Proc.*, vol. 153, pp. 1413–1442, 1987.

[4] S. Prabhakar *et al.*, "Observation and modal analysis of coupled-bunch longitudinal instabilities via a digital feedback control system," *Part. Accel.*, vol. 57, p. 175, 1997.

[5] D. Teytelman, *Architectures and algorithms for control and diagnostics of coupled-bunch instabilities in circular accelerators*. PhD thesis, Stanford University, 2003. SLAC-R-633.