MOPP028

Longitudinal Bunch-by-Bunch Feedback Systems for SuperKEKB LER

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Abstract

Longitudinal bunch-by-bunch feedback systems to suppress coupled bunch instabilities with minimum bunch spacing of 2 ns have been constructed in SuperKEKB LER. Through the grow-damp and excite-damp experiments with several filling patterns and the transient-domain analysis of unstable modes, the behaviors of possible impedance sources have been evaluated. The measured performance of the system, together with the performance of the related systems such as slow phase feedback to the reference RF clock are reported.

Introduction

Target of SuperKEKB collider:

Design target : Realize x40 luminosity of KEKB

with 1/20 of IP vertical beam size

x2 of beam currents

Phase-1: without IP

Phase-2 : with IP, Belle II detector and final focus system, without innermost detectors (SVD, Pixel)

Phase-3: Almost full set of detectors: Luminosity production

Longitudinal coupled-bunch instability (CBI)

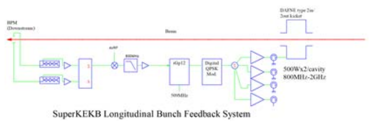
Fundamental modes (-1, -2, ..): Mode-by-mode FB in LLRF

Cavity induced instability : Anticipated growth time was slow: 21 ms@3.6A(LER)

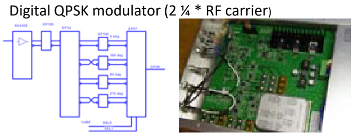
Observed unexpected L-CBI during Phase-1 and 2 with much lower beam current.

	HER	LER
Energy (GeV)	7	4
Circumference (m)	3016	
Maximum beam current (achieved, mA)	1010	870
Max. bunch current (achieved, mA)	1	1.5
Bunch length (mm)	5	6
RF frequency (MHz)	508.886	
Harmonic number	5120	
Typical synchrotron tune	0.028	0.024
Momentum compaction factor	4.5e-4	3.2e-4
Longitudinal radiation damping time (ms)	29	23
Natural horizontal emittance (nm)	4.6	3.2
Peak luminosity (achieved, cm^{-2} s^{-1})	1.23×10^{34}	
Longitudinal bunch feedback	0	1
Number of longitudinal kicker	0	4

Longitudinal bunch-by-bunch feedback system



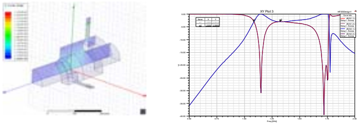
Digital QPSK modulator (2 ¼ * RF carrier)



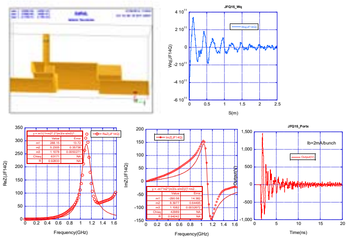
Colby switch delay (10ps step, max 2ns or 10ns)

Longitudinal Feedback Kicker (DAFNE type over-damped cavity)

ANSYS HFSS simulation



GdfidL simulation



Quality factor ~5 (3dB bandwidth ~ 240MHz)

Calculation of Rsh

1) Calculate the longitudinal E-field

$$E_z(z)=\sqrt{E_z^2(z,\Phi=0^\circ)+E_z^2(z,\Phi=90^\circ)}$$

$$\varphi_z(z)=\tan^{-1}\left(\frac{E_z(z,\Phi=90^\circ)}{E_z(z,\Phi=0^\circ)}\right)$$

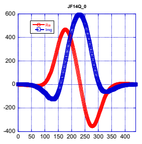
2) Calculate effect of transit time

$$\mathrm{Re}(V_g(\omega))=\int_{-L/2}^{L/2}E_z(z)\cos(\omega z/c-\phi_z(z))dz,$$

$$\mathrm{Im}(V_g(\omega))=\int_{-L/2}^{L/2}E_z(z)\sin(\omega z/c-\phi_z(z))dz$$

3) Integrate Real part and Imaginary part Int(Re)=10.2, Int(Im)=39.6, in this case

4) Rsh = V^2/2p, ->Rsh ~ 1.68kΩ



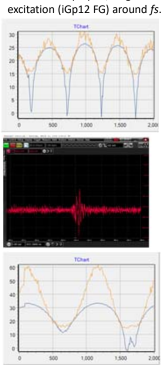
Input / Output ports	2/2
Center frequency	1.145 GHz
3dB bandwidth	240 MHz
Shut impedance	1.68 kΩ/cavity
Longitudinal loss factor	0.406 V/pC /cavity
Transverse kick factor	2.06 V/pC /m / cavity
Length (flange-to-flange)	0.44 m

Commissioning of the Longitudinal Bunch Feedback System

1) Tuned the timing and phase of the bunch phase detector, ADC timing of the iGp12.
2) The fine DAC timing within 2 ns of the iGp12 has been adjusted to synchronize the DAC output to the switch timing of the digital QPSK.

Fine sweep of feedback kicker timing

Feedback loop open, single bunch (pilot bunch) excitation (iGp12 FG) around *fs*.



LK3 only, 10ps /step

FFT Amplitude response of the *fs* of the target bunch

Peak (blue) and RMS (yellow)

Peak : 980 ps

Output of high-power ATT feedback signal appears roughly 1ns before the beam induced signal

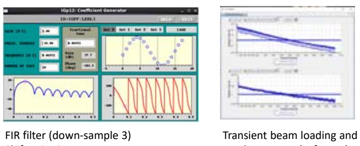
LK4 sweep, with LK3=980ps

Peak: 1170ps

Tune other kickers, LK1 and LK2 with LK3, to find the best delay.

Feedback phase, gain, etc

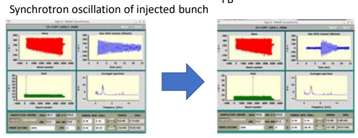
Close the feedback loop to find the negative feedback phase by changing the feedback phase of FIR filter in the iGp12. The fine tuning, including the feedback gain (shift gain in the iGp12) has been performed using beam with excite-damp (or grow-damp) scheme.



FIR filter (down-sample 3)
Shift gain=3

Transient beam loading and RF phase servo (software) to 4xRF (2GHz) source for FB

Synchrotron oscillation of injected bunch



LFB OFF — LFB ON

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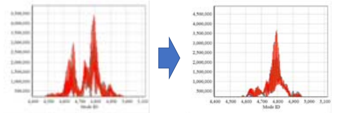
Longitudinal Coupled-Bunch Instability

Observed longitudinal CBI during Phase-1 and Phase-2

- Unexpected low threshold beam current
- Threshold current strongly depends on the filling pattern
  - 150 mA with by 2 filling pattern, unstable modes around -330
  - 800 mA with by 3.06 filling pattern
- Another set of unstable modes around mode -470 appeared with dependence of the gap width of the horizontal collimator nearest to interaction point D2H4.

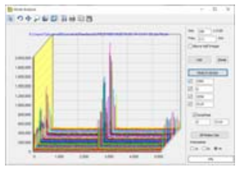


Change of longitudinal unstable mode with half gap=13mm (left) and half gap=9.5mm (right). Mode around -470 vanished with the narrower gap.

Phase-3 operation

No spontaneous CBI (other than fundamental modes) has been observed up to:

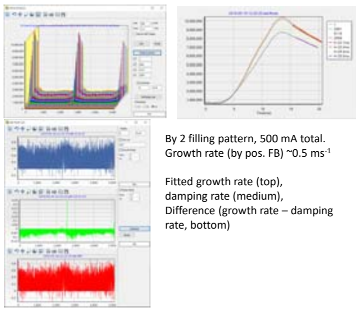
- 500 mA with by 2 filling pattern
- 575 mA with by 3 filling pattern



Unstable modes with by 2 filling pattern, total beam current tof 500 mA LFB OFF
(Horizontal: Mode ID, Vertical: Amplitude, Depth, Time evolution from 0ms to 22ms)
Only mode 0(noise?), -1 and -2 has appeared.

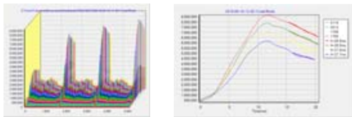
Longitudinal Feedback Experiments at Phase-3

Transient-domain analysis(1)
Excite(pos. FB)->FB OFF(radiation damping)



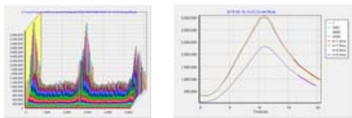
By 2 filling pattern, 500 mA total. Growth rate (by pos. FB) ~0.5 ms^{-1}

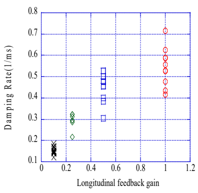
Fitted growth rate (top), damping rate (medium), Difference (growth rate – damping rate, bottom)



Example excite-free experiment of by 3 filling pattern

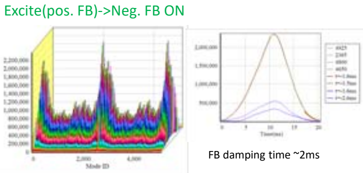
Transient-domain analysis(2)
Excite(pos. FB)->Neg. FB ON(FB gain change)





Change of the feedback damping rate with the longitudinal feedback gain. Clearly the damping rate shows linear dependence with feedback gain

Transient-domain analysis(3)
Excite(pos. FB)->Neg. FB ON

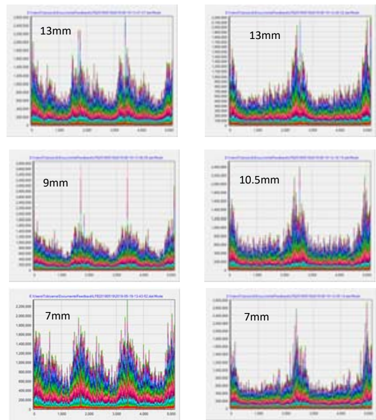


FB damping time ~2ms

Transient-domain analysis(4)
Effect of gap width of D2H4 with Excite-damp

Example of mode pattern of by 3 filling pattern with several half gap of D2H4

Example of mode pattern of by 2 filling pattern with several half gap of D2H4



No obvious dependences on the gap of D2H4 has seen.

During normal operation (Luminosity runs) and special filling pattern with large bunch current, 1.5mA/bunch at ECI experiment

- Kept LFB and phase servo loop for 2GHz master for bunch feedback system ON.
- Until the maximum beam current of 830 mA on Phase-3 operation, no indication of longitudinal CBI which could not be suppressed by the LFB.
- During the e-cloud study (ECI experiment) with much larger bunch current, shorter length of bunch train, though we have observed not so fast longitudinal CBI other than the fundamental modes (-1, -2), it was completely suppressed with the LFB. The recapture of the feedback after grow-damp experiment (10 ms FB-OFF) was not difficult where at larger amplitude the final feedback amplifiers were already saturated with the current feedback gain (Bang-bang damping region) .
- No significant difficulties in the LFB hardware has been found during operation. The temperatures of the power components (such as feedthroughs, dummy loads, cables, high-power components) were well controlled by the external water cooling.

Summary

We have commissioned the longitudinal bunch-by-bunch feedback system in SuperKEKB LER. The damping rates achieved have been confirmed to scale linearly with the feedback gain. The longitudinal CBI observed during Phase-1 and Phase-2 operation was not reproduced in Phase-3 tests to date, but in all these tests the LFB system worked very well to stabilize the longitudinal motion during the colliding operation and the machine developments.

The authors would like to express their sincere appreciation to the commissioning group of SuperKEKB for their help in the operation and machine developments.