# Impedance and instability studies at SuperKEKB

K. Ohmi (KEK) eeFACT2022, Frascati, Italy Sep. 12-15, 2022

Thanks to H. Fukuma, T. Ishibashi, S. Terui, M. Tobiyama, D. Zhou

# Beam size blow up in positron ring, LER

- LER beam size blow up has been observed since early stage of commissioning in 2021.
- A series of measurement has been done in 2021-2022.
- The beam size blowup is single-beam and single-bunch effect. Check for Number of bunch=33,66,99,1567.
- It disappear when collimator open (lower impedance).
- It appears at  $v_y < 0.6$  and is serious at  $v_y < 0.58$ .
  - The idea, in which a localized impedance contributes, was rejected, because of FB response.
- It seemed to be related to the sideband of x-y coupling  $(v_x v_y v_s = n)$ .
  - The idea was rejected, see next.
- -1  $(v_y v_s)$  mode signal was seen at the blowup.
- The blow-up was suppressed at BxB feedback OFF.

#### Tune shift



	v <sub>y</sub> = 0.5890 (model), Σβ <sub>y</sub> k <sub>y</sub> =3.33e+16 V/C (calc), 2022-02-24
-	fit: y=(-1.08e-02)x + (0.5915), Σβ <sub>y</sub> k <sub>y</sub> =5.40e+16 V/C
	v <sub>y</sub> = 0.5890 (model), Σβ <sub>y</sub> k <sub>y</sub> =4.25e+16 V/C (calc), 2022-02-24
-	fit: y=(-1.43e-02)x + (0.5899), Σβ <sub>y</sub> k <sub>y</sub> =7.13e+16 V/C
	ν <sub>y</sub> = 0.5890 (model), Σβ <sub>y</sub> k <sub>y</sub> =1.80e+16 V/C (calc), 2022-02-24
-	fit: y=(-6.56e-03)x + (0.5892), Σβ <sub>y</sub> k <sub>y</sub> =3.28e+16 V/C
	ν <sub>y</sub> = 0.5890 (model), Σβ <sub>y</sub> k <sub>y</sub> =3.86e+16 V/C (calc), 2022-02-24
-	fit: y=(-1.27e-02)x + (0.5902), Σβ <sub>y</sub> k <sub>y</sub> =6.34e+16 V/C

$$\Delta \nu_{\beta} = 2.00 \times 10^{-19} \sum_{i} \beta_{i} K_{\perp i} I(mA)$$

Collimator set in the beam size measurement is  $\Delta\nu_{v}{=}0.01{\text{-}}0.013/\text{mA}$ 



- The stop-band is remarkably spread when the instability occurs.
- The vertical emittance is getting smaller for higher vertical tunes.
- We can see a small stop-band around 0.595 with the middle bunch current of 0.72 mA/bunch ( $v_x = 0.5310$ ).
- It had been difficult to inject in  $v_y = 0.6$  or above, and the vertical emittance decreases at the higher vertical tune. 4

#### Tune Survey



Vertical Tune Scan For High Current

- The structure of the stop-bands in the lower and higher  $v_{x}$  is exactly same. ٠
- This probably indicates that the chromatic coupling ( $v_y v_x + 2v_s = N$  line) is not related to this ٠ instability.

# Bunch Oscillation Recorder spectra

- Tune 0.524,0.590, 100bunch, I=0.3-1.1mA/b.
- $\bullet$  Emittance growth and tune peak  ${\sim}0.57$  appear



#### BOR and Pilot bunch spectra

Pilot bunch: Tail bunch, BxB feedback inactive



Courtesy H. Fukuma

# Gated tune and BOR

- Gated tune of the pilot bunch, tune  $v_v$  and sideband  $v_v$ - $v_s$ .
- BOR data of whole bunches
- Peak seen in BOR is -1 mode  $v_{y}$ - $v_{s}$



Courtesy H. Fukuma

# Vertical Emittance w/wo D06V1



- When we fully opened the aperture of D06V1, the vertical emittance blow-up didn't occur up to  $\sim$ 1.5 mA/bunch.
  - > (D06V1 aperture) close:  $\pm 2.9$  mm, open:  $\pm 8$  mm
- The background level derived from the storage beam increased when we opened it. We've used D06V1 as a primary collimator to cut off the injection backgrounds, but these observations indicate this collimator contribute to suppress the storage backgrounds too. • g

# Vertical Emittance w/wo BxB FB (Mar. 1st) 33-bunch operation



- We observed the vertical emittance with turning on/off the feedback (FB) with small number of the bunches to avoid multi-bunch instabilities.
- When we turned on the FB, the blow-up occurred around 0.85 mA/bunch.
- When we turned off the bunch-by-bunch FB, the vertical emittance blow-up didn't occur up to around 1.06 mA/bunch (poor injection rate above than this current).
- After the tuning of the FB to suppress the "-1 mode instability", the blow-up didn't occur up to ~1.44 mA/bunch (design bunch current in LER).

# Vertical Emittance w/wo BxB FB

[M. Tobiyama]



- Two FB loops have been tuned to suppress f<sub>3</sub> line (99.8-41 kHz) with resistive kick, but the FB becomes reactive for the f<sub>3</sub>-f<sub>5</sub> line at 99.8-43 kHz. This enhances the -1 mode instability. The instability has occurred whether we turn on the FB or not (but with different thresholds).
- M. Tobiyama tuned the phase of one loop by changing the FB filter to suppress the f<sub>β</sub>-f<sub>s</sub> line, and this suppresses the instability with 1dB of the FB gain. However, the FB becomes reactive for betatron frequency line (0 mode).

# Mechanism of the beam size blowup

- Beam size increases when -1 mode appears at ~0.9mA.
- The 0 and -1 modes are not coupled at the current. The threshold of TMCI is ~2mA.
- Studies considering both the impedance and bunch-bybunch feedback are necessary.

#### Wake force used in simulations (prepared by D. Zhou, T. Ishibashi)

- Kick Factor  $\beta_y K_y$ ,  $\beta_y K_{qy}$  (V/C)
  - GdFidI -3.84x10<sup>16</sup>, -1.27x10<sup>16</sup>  $\Delta v_y = 0.01/mA$
  - ECHO3D -3.18x10<sup>16</sup>, -0.84x10<sup>16</sup>  $\bigcirc$  $\Delta v_y = 0.008/mA$ . Multiply 1.25 to  $\bigcirc$ get measured tune shift  $\Delta v_y = 0.01/mA$

$$\Delta \nu_{\beta} = 2.00 \times 10^{-19} \sum_{i} \beta_{i} K_{\perp i} I(mA)$$



-20

-10

z (mm)

0

10

-3000

-30



#### Simulation without feedback



• No emittance increase.

0 mode is seen. Tune shift is 0.01/mA

Bunch by Bunch feedback system in SuperKEKB-LER

- 2 feed back loop working independently, TFBK1-FBMON1 and TFBK2-FBMON2
- Max 10 tap

AX ΒX NX Element Length .67792 19.5518 21.9781 PF7TFBK1 .00000 .69845 19.9303 21.9759 FZTFBKP1 .55000 .56341 17.6476 21.9913 PFZTFBK2 .00000 .58394 17.9631 21.9888 FZTFBKP2 .55000 .49527 23.9306 22.0432 PFBMON1 .00000 -.49527 23.9306 22.1906 PFBMON2 .00000 -.60424 18.2863 22.2474 PFZLFBK1 .00000 -.70726 20.0962 22.2588 PFZLFBK2 .00000 1.71319 14.6430 27.4756 PMD06V1 00000 0.0000 .08000 44.5250 IP .00000

s(m)	AY	ΒY	NY	#	ΕX	EPX	
1489.30431	-1.1407	6.31089	22.7721	4006			
1489.02931	-1.0404	5.71108	22.7648	4007			
1490.83831	-1.7000	10.6686	22.8020	4009			
1490.56331	-1.5997	9.76118	22.7977	4010			
1499.90944	.84750	19.4097	22.9117	4034			
519.05569	84750	19.4097	23.1355	4046			
1528.67382	1.50061	8.91787	23.2541	4070			
1530.05382	.99740	5.47061	23.2857	4073			
1870.26828	-10.133	67.3498	28.8574	4660	.516	0728	
3016.30649	0.0000	.00100	46.5870	8097			

# model for SuperKEKB

- Betatron phase difference
- φ<sub>y</sub>(M1)=22.9117, φ<sub>y</sub>(K1)=22.7721
- $\Delta \phi_y (M1 -> K1) = 46.4474$
- φ<sub>y</sub>(M2)=23.1355, φ<sub>y</sub>(K2)= 22.8020
- $\Delta \phi_y$ (M2->K2)= 46.2535



#### FIR digital filter

$$\Delta P_{K}(n) = \sum_{k=0}^{(N_{tap}-1)} c_{oef}(k) X(n-k)$$

Example of actual setting of the filter coefficients

- Filter coefficients (~Mar. 11, 2022)
  - coef1={21623,-5530,-11430, 25925,-32767, 31362,-20832, 5288, 12317,-25956};
  - coef2={26781,-26182, 7149, 2479,-22777, 25564,-32767, 19752};
- Filter coefficients (~Mar. 12, 2022)
  - coef1={29144,-32767,-16328, 19950};
  - coef2={10883,-32767, 28452,-20750,-7342, 21524};

#### Resistive and reactive components for FIR filter

$$\Delta P_K(n) = \sum_{k=0}^{(N_{tap}-1)} c_{oef}(k) X(n-k) = -2d_P P_K(n) - 2d_X X_K(n)$$

• Relation of X(n-k) and X<sub>K</sub>(n), P<sub>K</sub>(n) are associated through the betatron motion with the tune  $\mu=2\pi\nu$ .

 $X(n-k) = Re[(X_K(n) + iP_K(n))\exp(ik\mu + i\Delta\phi)] = X_K(n)\cos(k\mu + \Delta\phi) - P_K(n)\sin(k\mu + \Delta\phi)$ 

• Resistive and reactive components for FIR filter

$$d_{P} = \frac{1}{2} \sum_{k=0}^{(N_{tap}-1)} c_{oef}(k) \sin(k\mu + \Delta \phi) \qquad \qquad d_{X} = -\frac{1}{2} \sum_{k=0}^{(N_{tap}-1)} c_{oef}(k) \cos(k\mu + \Delta \phi)$$

- For Ntap=1,  $\Delta \phi = \pi/2$  is pure resistive,  $\Delta \phi = \pi$  is pure reactive.
- In general, resistive and reactive components are mixed.
- For tune scan,  $\mu = 2\pi(\nu_0 + \delta \nu)$ ,  $\Delta \phi = 2\pi(\Delta \phi_0 + \delta \nu)$ , where betatron phase is changed at the section from the monitor to the kicker.

#### Resistive and reactive components

- Filter coefficients (~Mar. 11, 2022)
  - coef1={21623,-5530,-11430, 25925,-32767, 31362,-20832, 5288, 12317,-25956};
  - coef2={26781,-26182, 7149, 2479,-22777, 25564,-32767, 19752};





- (Mar.12, 2022)
  - coefU={29144,-32767,-16328, 19950};
  - coefD={10883,-32767, 28452,-20750,-7342, 21524};





# Simulation BxB feedback ON

• The simulation considers the betatron phase phases of monitors, kickers and D6V1 collimator.



# Vertical emittance and FFTy at I=0.5mA

• First FBcoef (Mar. 11)



No emittance increase at low current

# Vertical emittance and FFT of <y>

- Second FBcoef (Mar. 12)
- I=1mA/b
- Emittance increase at low  $v_v$  is suppressed.



# 1 tap resistive feedback

- Simplest feedback model
- Use  $2^{nd}$  feedback loop, FB gain 0.1. No growth at G=0.15.
- Choose  $\phi(K2) = \phi(M1) + 0.25 v_y(0.585)$ .
- No emittance increase. -1 mode is seen.



# Summary for feedback

- Multitap (1st coef) and high gain feedback system (G=0.1) cause 1 mode instability.
- Multitap FB with  $2^{nd}$  coef. and 1 tap FB (G=0.1) does not cause -1 mode instability.
- These explain the experimental results.
- The High gain G~0.1 may be controversial.
  - Feedback may kick a bunch stronger than  $dp_y = -Gy$  at a small amp., y.
- Effect of monitor resolution and kicker error/noise will be studied.

# Effects of collimator offset

- Dipole kick depends on the longitudinal distribution
- Turn-by-turn change of y-z distribution for collimator offset 3mm at D6V1 is shown.
- An equilibrium distribution with a banana shape is formed after several radiation damping time.



#### BxB FeedBack OFF with collimator offset 1mm

- Emittance increases 30->40pm at 1mA/b for collimator offset 1mm at D6V1.
- This may explain small emittance increase for the bunch current.
- Equilibrium orbit distortion as function of z.  $< y >= 0.3\sigma_y$ ,  $< yz >= 0.1\sigma_y\sigma_z$ .
- No large emittance growth for the tune scan, 0.565<ny<0.585.





20000

20 25

#### BxB feedback ON with collimator offset 1mm

- Filter coefficients (~Mar. 11, 2022)
- FB gain(damping rate) 0.05(FB1)+0.05(FB2)
- Emittance growth is seen at low  $v_{v}$ .
- -1 mode is seen at every tune.



• No remarkable change from the case without collimator offset.

# Summary

- -1 mode instability, which is single beam and single bunch phenomenon, occurs high bunch current, narrow collimator aperture ( $\Delta v_y > 0.01$ ) and BxB feed back ON.
- The instability can be suppressed by tuning of the feedback.
- The instability strength is changed by condition of BxB feedback and impedance damage.
- The instability can be reproduced by simulation using transverse wake and high gain multi-tap feedback.
- Higher  $v_y > 0.58$  is preferred for the instability, but injection is worse in the high vertical tune.
- This instability sometimes causes troubles in the physics operation due to condition of feedback and collimator and careless tune change.



• Collision condition becomes worse when V tune go down carelessly.

# Thank you for your attention