-1 mode instability at SuperKEKB LER

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Mini-workshop on impedance modeling and impedance effects at SuperKEKB and future colliders,
Dec.15-16, 2022

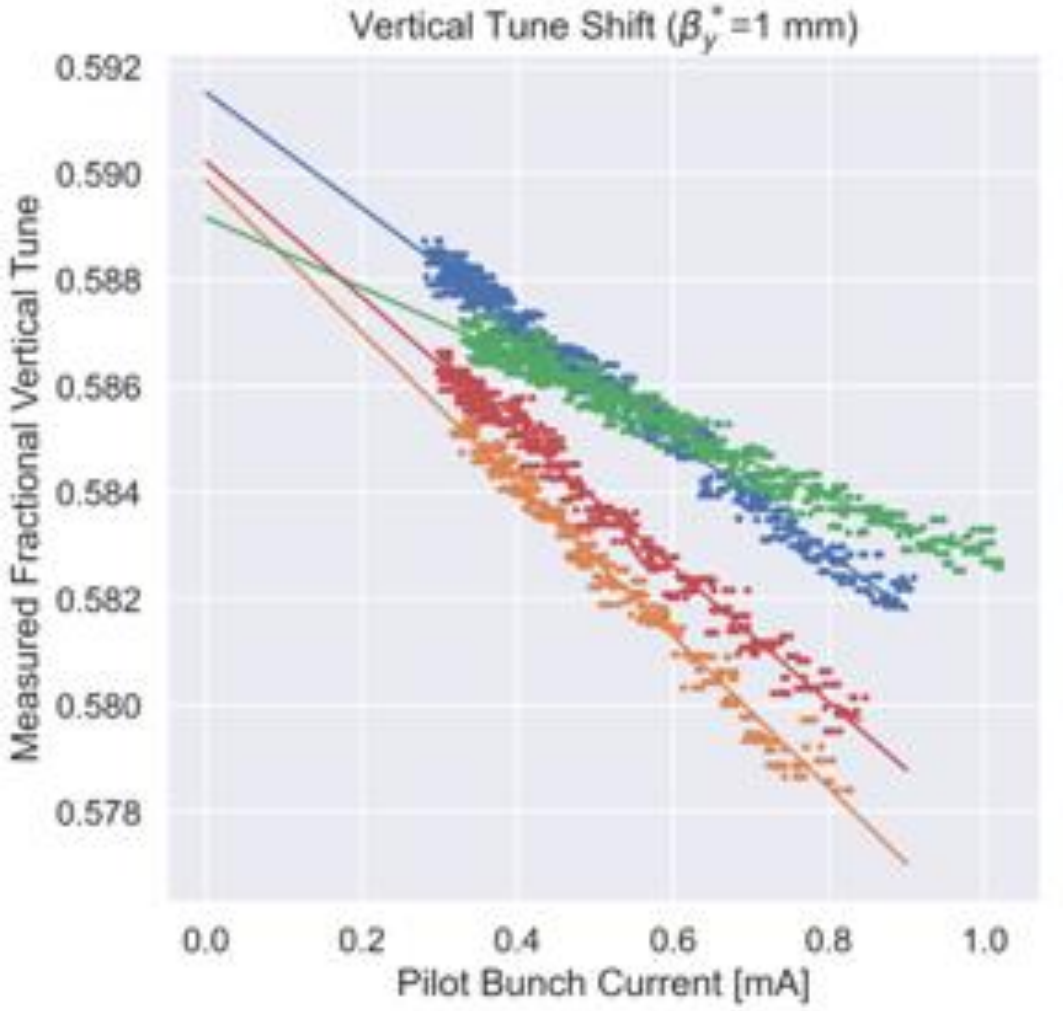
Accelerator Review Committee of SuperKEKB
Dec. 13-14, 2022

Thanks to H. Fukuma, T. Ishibashi, M. Migliorati, 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. Independent of Number of bunch=33,66,99,1567.
- It disappear when collimator open (reduced impedance).
- It appears at ν_y<0.6 and is serious at ν_y <0.58.
  - The idea, in which a localized impedance contributes, was rejected, because of Feed Back response.
- It seemed to be related to the sideband of x-y coupling (ν_x - ν_y - ν_s =n).
  - The idea was rejected, see next.
- -1 (ν_y-ν_s) mode signal was seen at the blowup.
- The blow-up was disappeared at BxB feedback OFF.

Tune shift



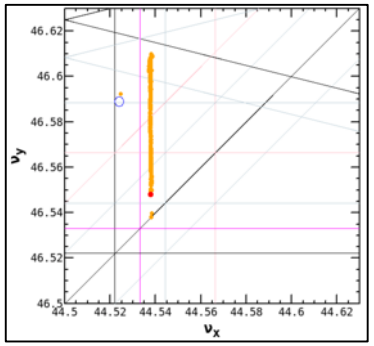
- ν_y = 0.5890 (model), $\Sigma\beta_y k_y$=3.33e+16 V/C (calc), 2022-02-24
- fit: y=(-1.08e-02)x + (0.5915), $\Sigma\beta_y k_y$=5.40e+16 V/C
- ν_y = 0.5890 (model), $\Sigma\beta_y k_y$=4.25e+16 V/C (calc), 2022-02-24
- fit: y=(-1.43e-02)x + (0.5899), $\Sigma\beta_y k_y$=7.13e+16 V/C
- ν_y = 0.5890 (model), $\Sigma\beta_y k_y$=1.80e+16 V/C (calc), 2022-02-24
- fit: y=(-6.56e-03)x + (0.5892), $\Sigma\beta_y k_y$=3.28e+16 V/C
- ν_y = 0.5890 (model), $\Sigma\beta_y k_y$=3.86e+16 V/C (calc), 2022-02-24
- fit: y=(-1.27e-02)x + (0.5902), $\Sigma\beta_y k_y$=6.34e+16 V/C

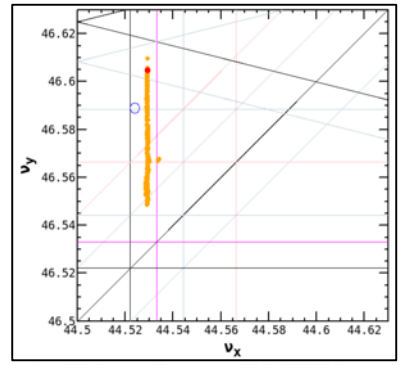
$$\Delta\nu_\beta = 2.00 \times 10^{-19} \sum_i \beta_i K_{\perp i} I(mA)$$

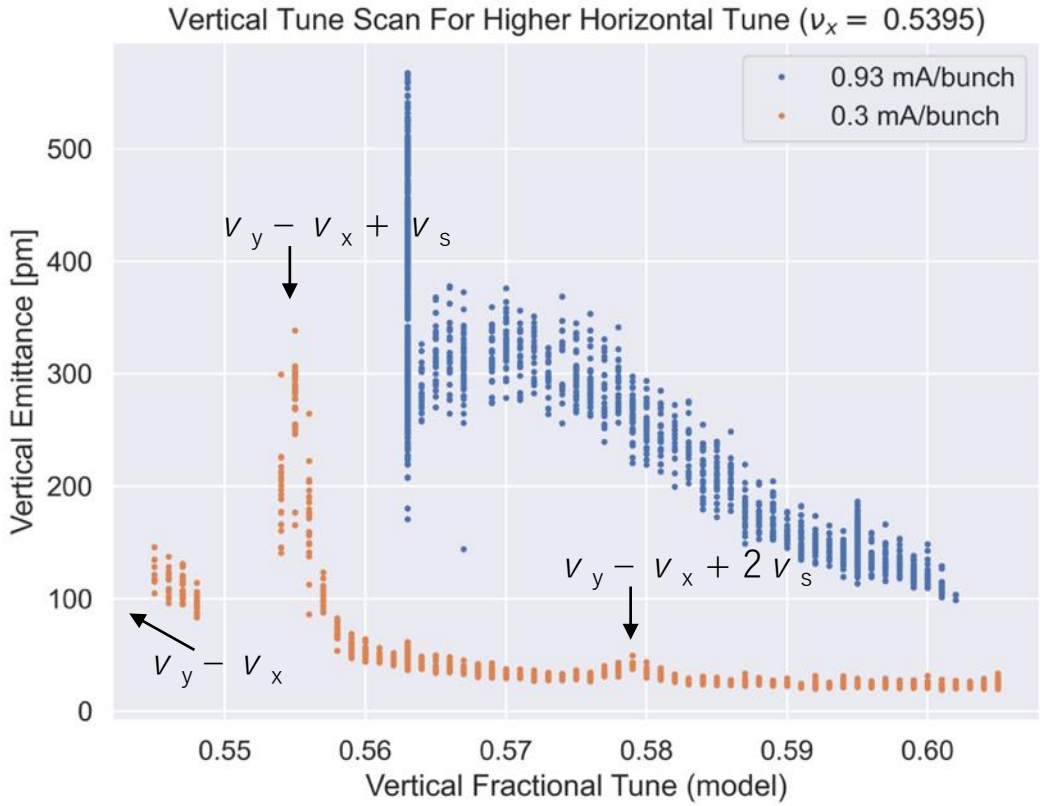
Collimator set in the beam size measurement is $\Delta\nu_y$=0.01-0.013/mA

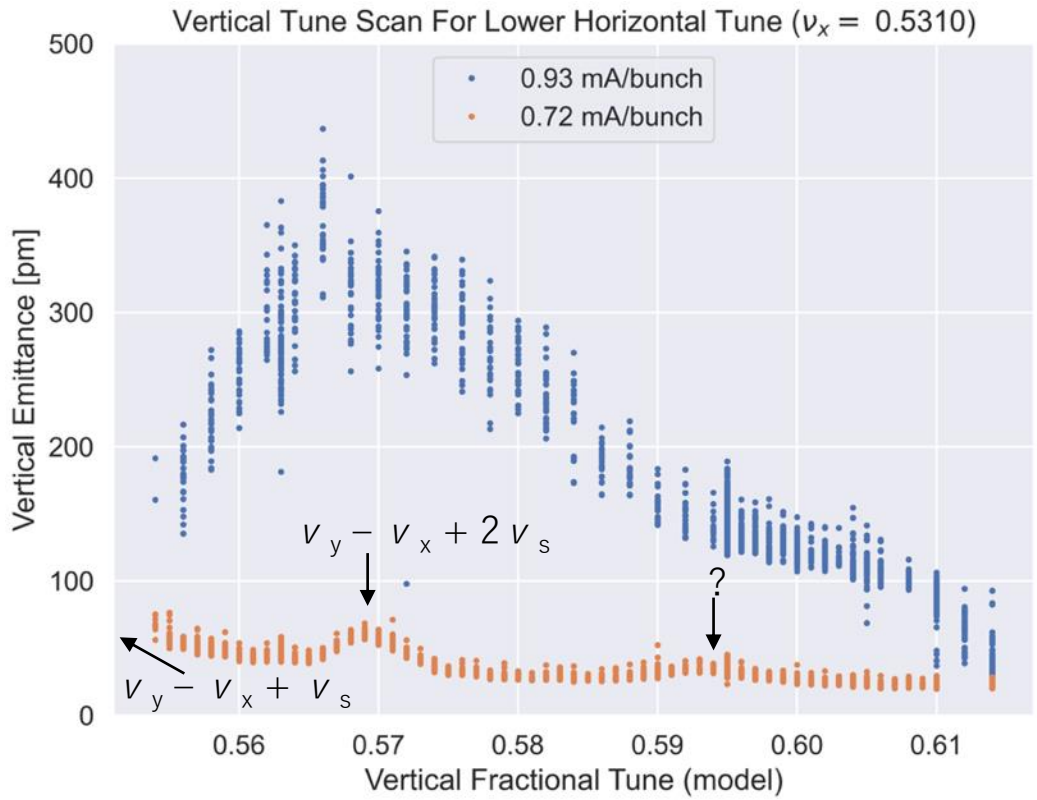
Tune Survey

No collision
Set kβ=36.1x10^{15} V/C



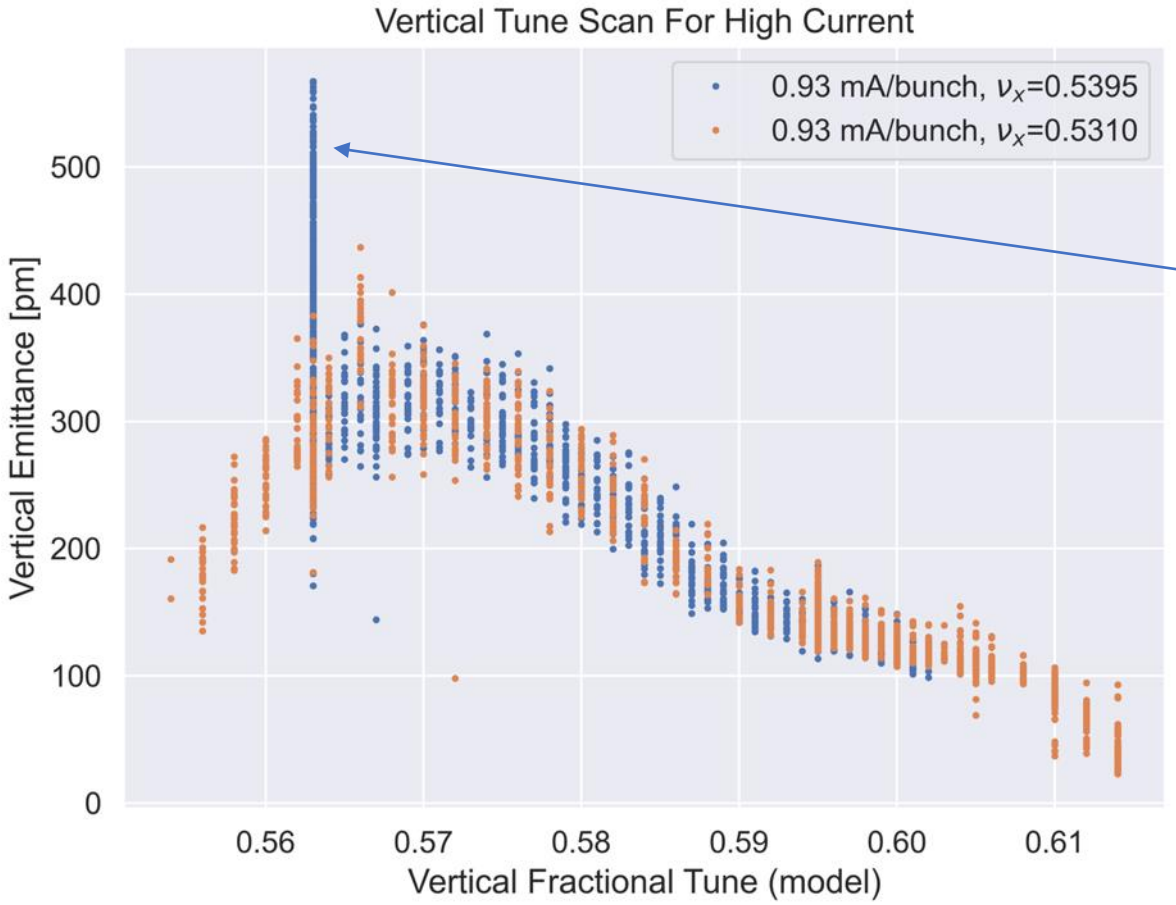






- The stop-band is remarkably spread when the instability occurs.
- The vertical emittance is getting smaller for higher vertical tunes.
- We can see a small stop-band around 0.595 with the middle bunch current of 0.72 mA/bunch (ν_x = 0.5310).
- It had been difficult to inject in ν_y = 0.6 or above,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

Tune Survey

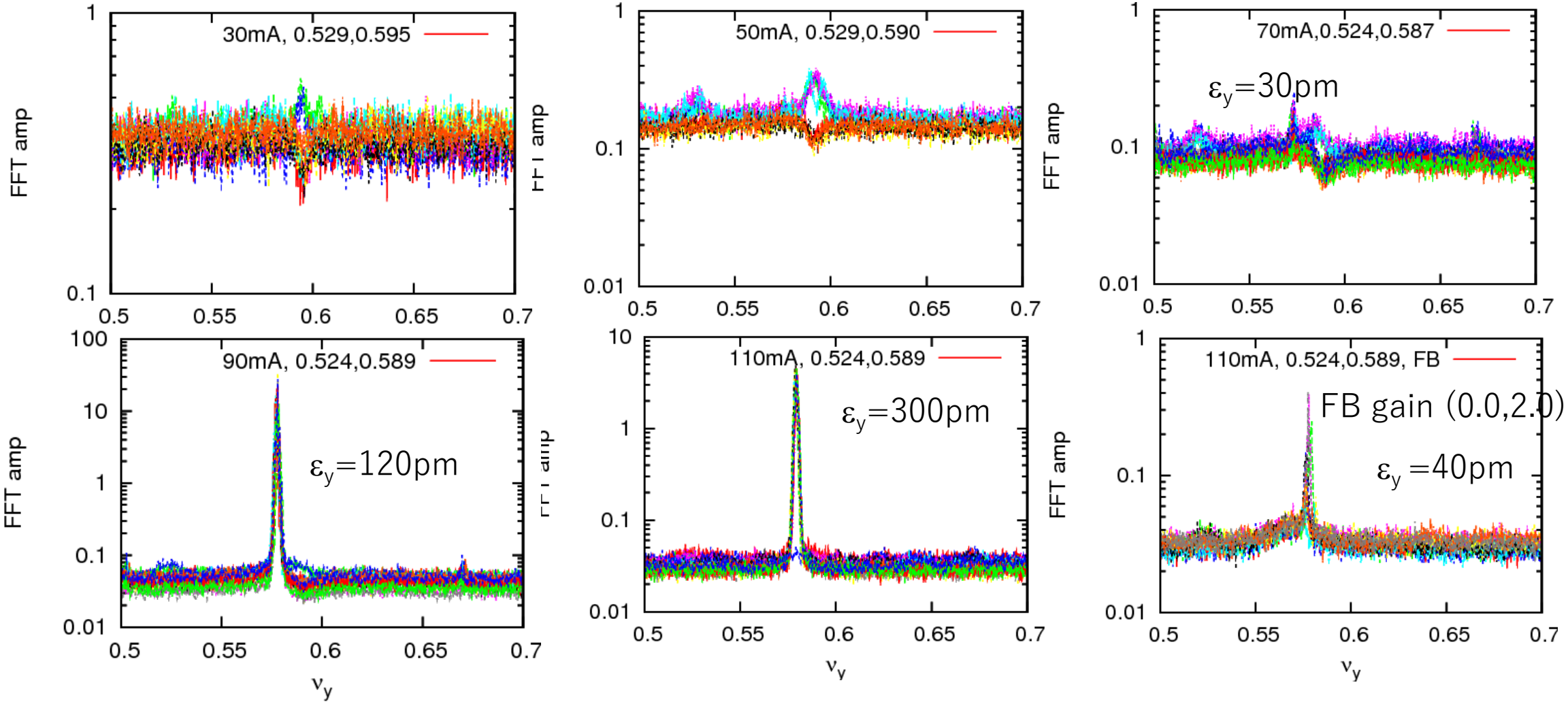


Troubles on beam injection, irrelevant to beam instability.

- The structure of the stop-bands in the lower and higher ν_x is exactly same.
- This probably indicates that the chromatic coupling ($\nu_y - \nu_x + 2\nu_s$=N line) is not related to this instability.

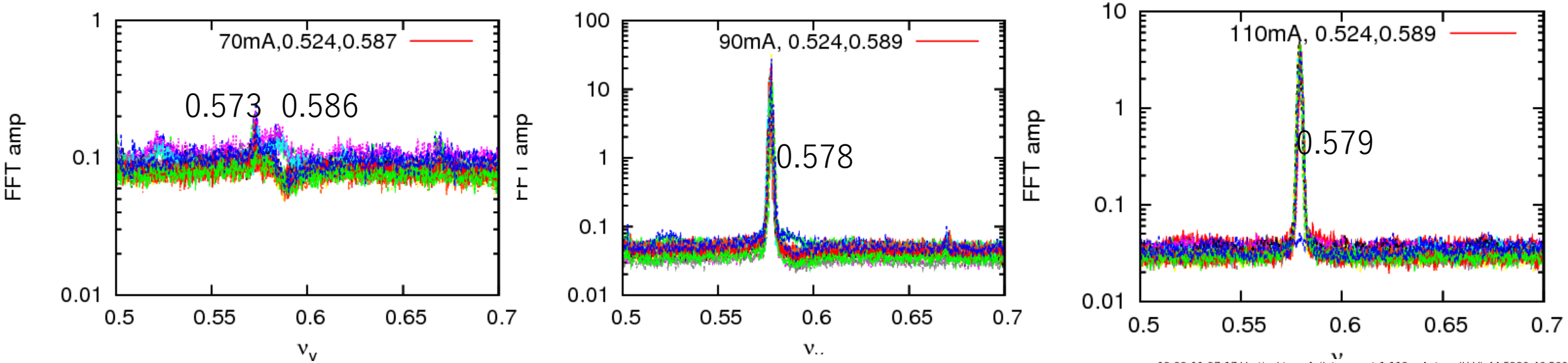
Bunch Oscillation Recorder spectra

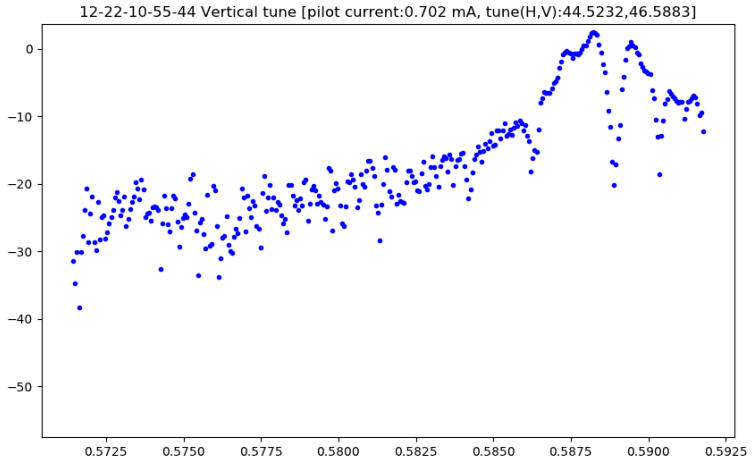
- Tune 0.524,0.590, 100bunch, I=0.3-1.1mA/b.
- Emittance growth and tune peak ~0.57 appear simultaneously.

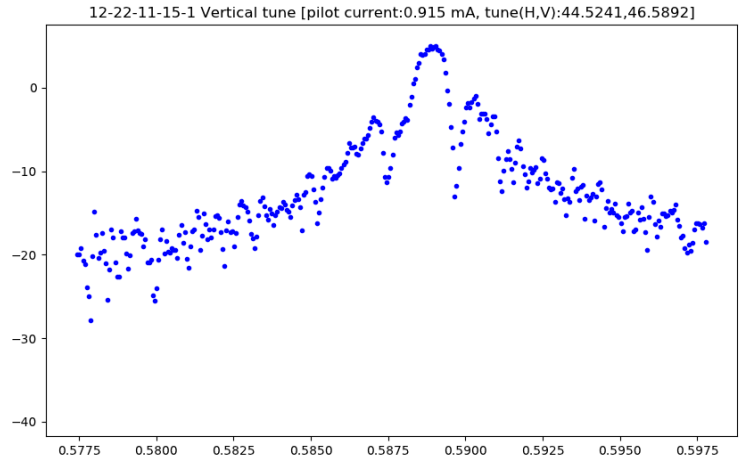


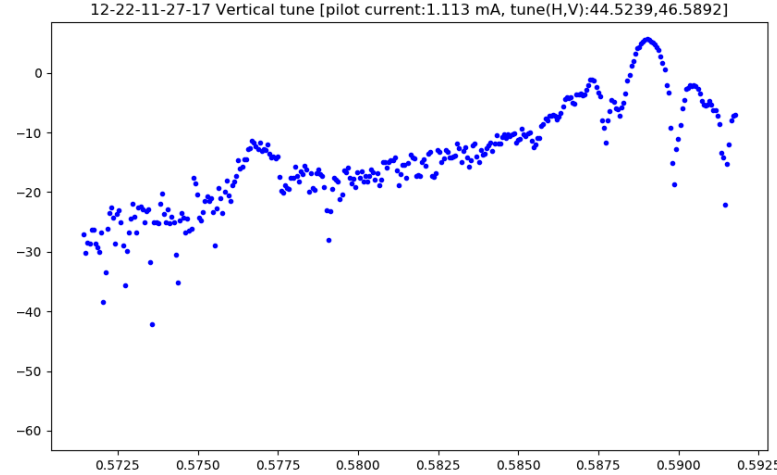
BOR and Pilot bunch spectra (0 mode)

Pilot bunch: Tail bunch, is shaked by frequencies scanned, BxB feedback inactive







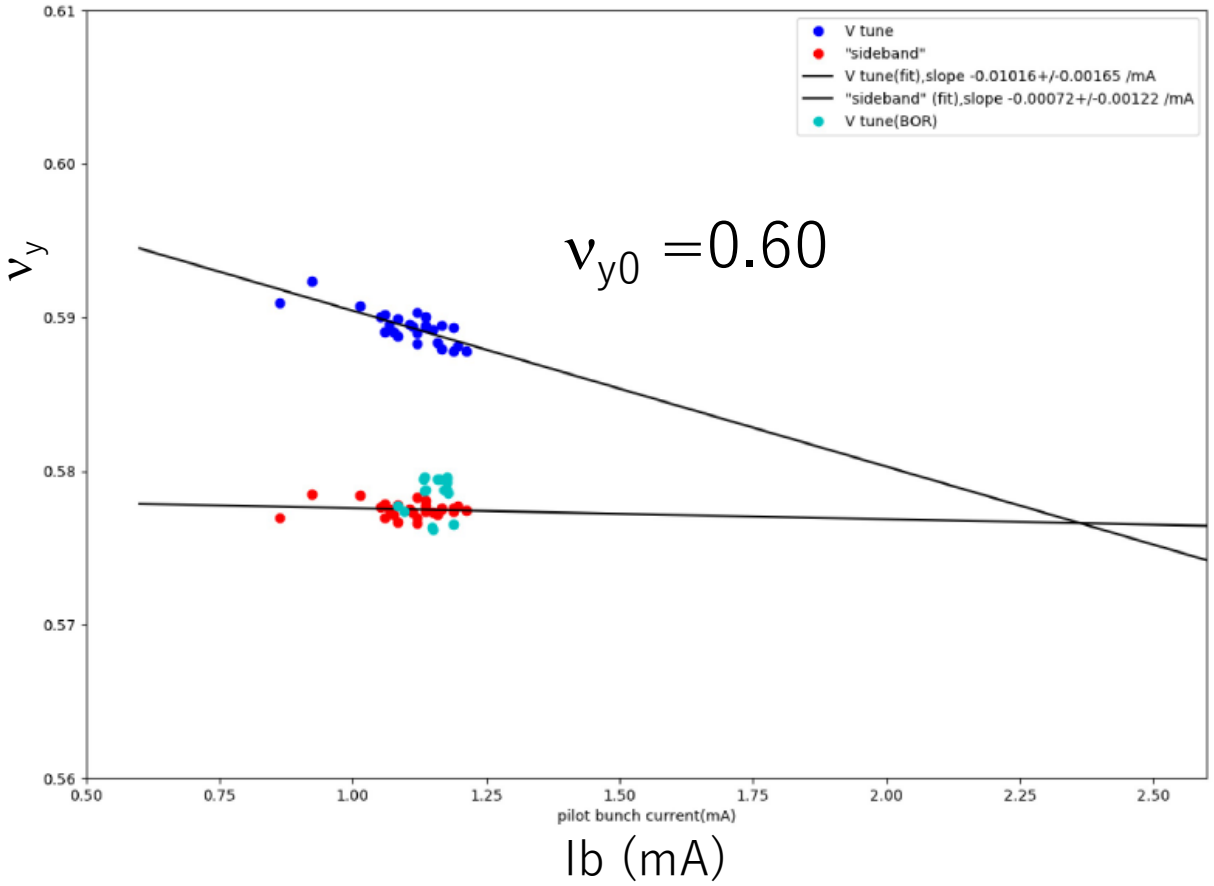


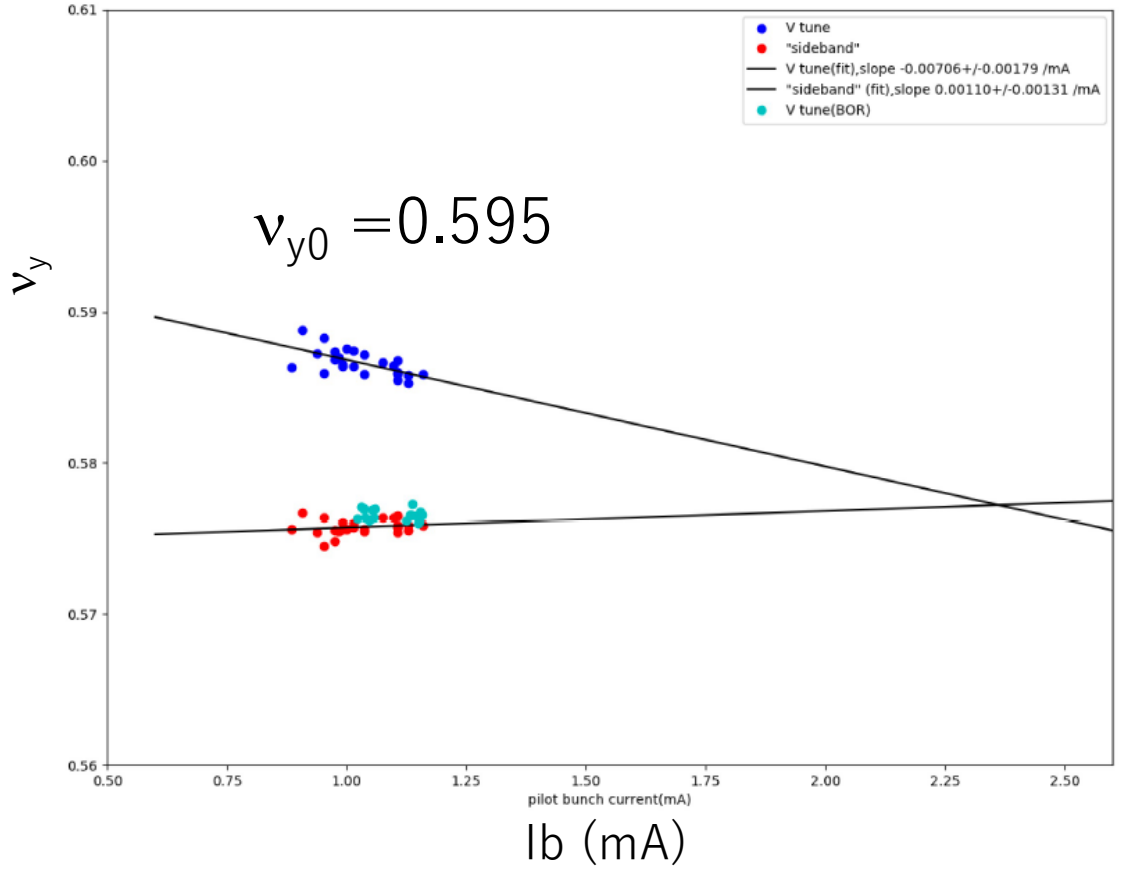
Courtesy H. Fukuma

Gated tune and BOR

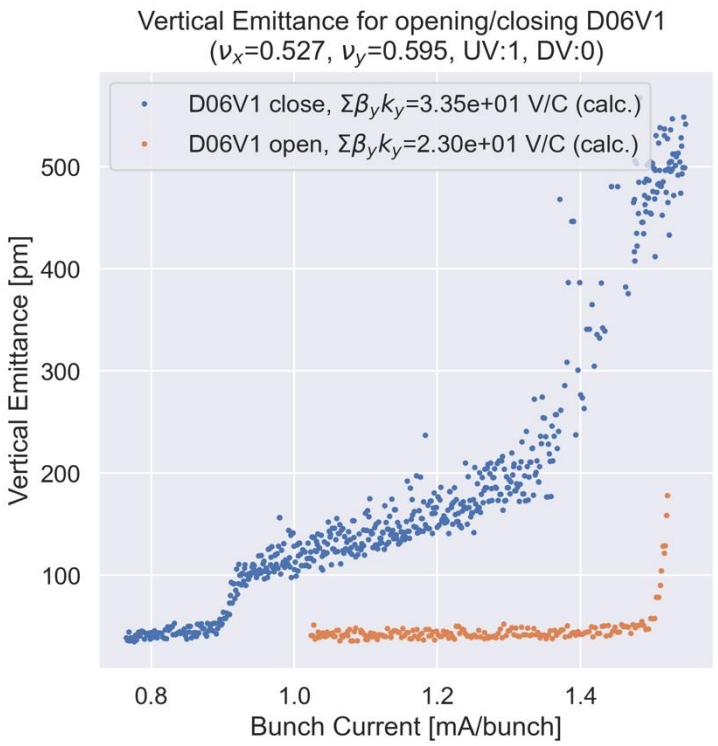
- Gated tune of the pilot bunch, tune ν_y and sideband ν_y-ν_s.
- BOR data of whole bunches
- Peak seen in BOR is -1 mode ν_y-ν_s

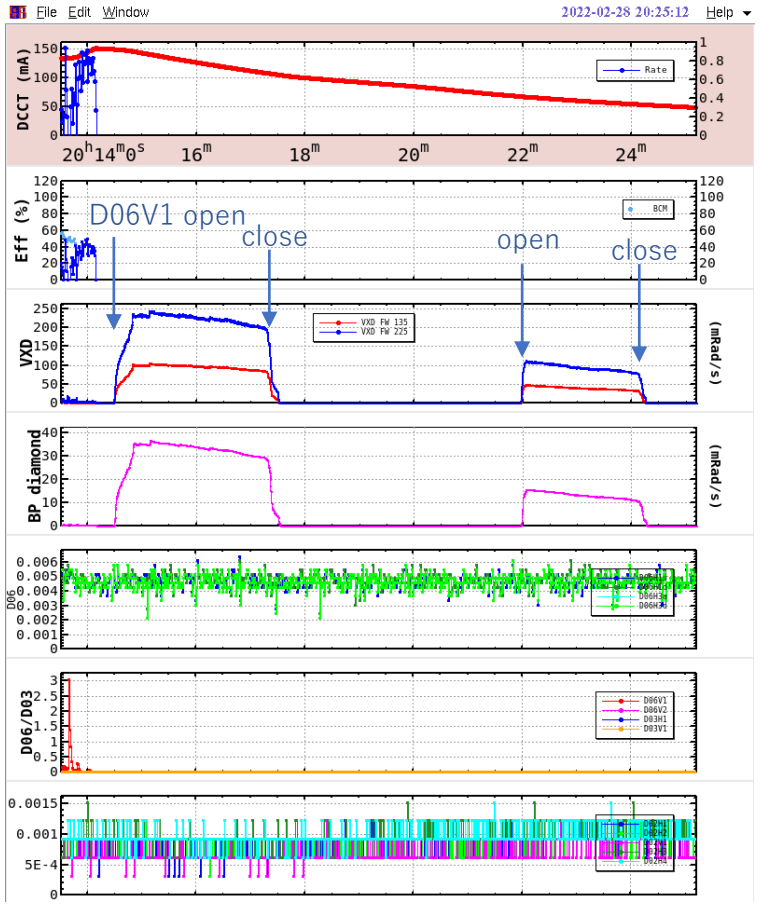
Courtesy H. Fukuma

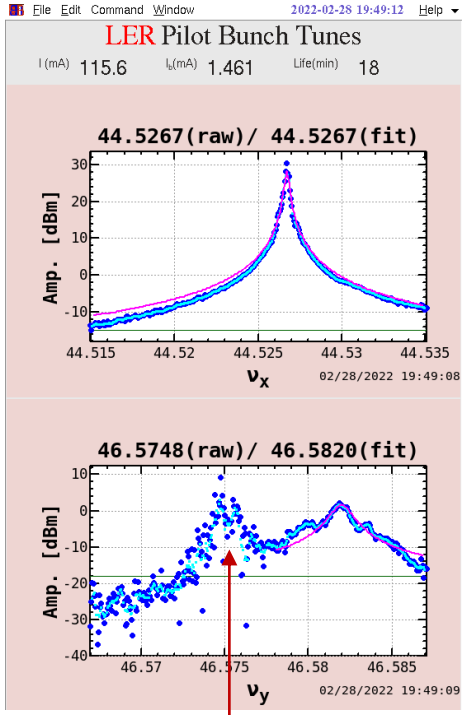


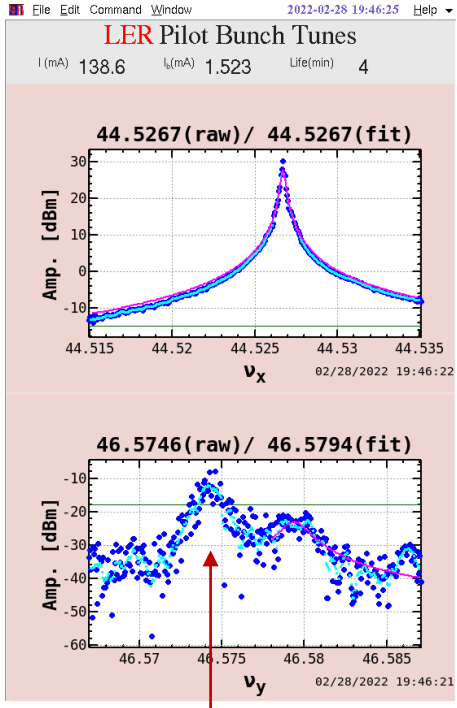


Vertical Emittance w/wo D06V1









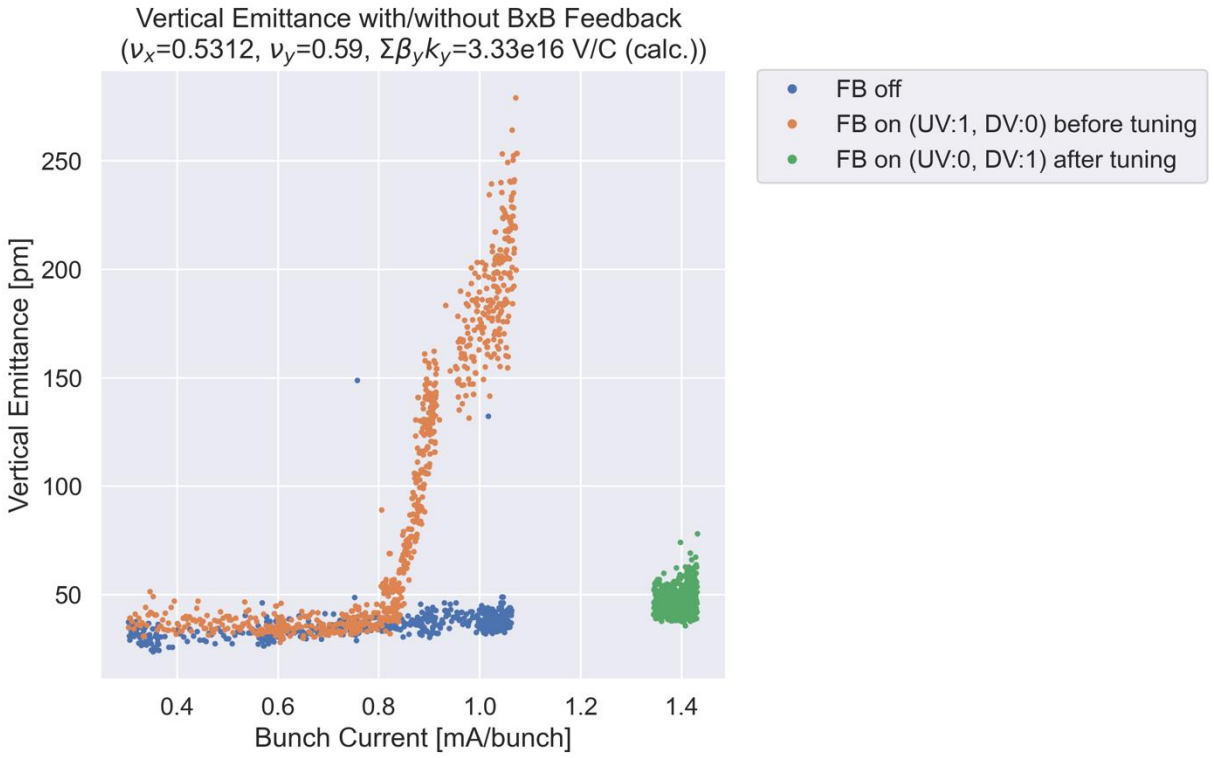
side-band

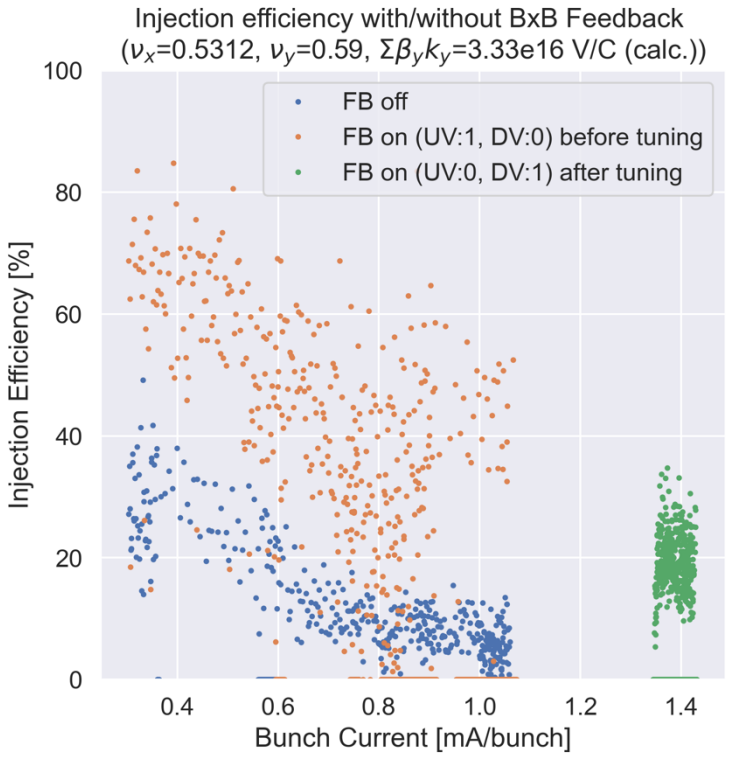
side-band

- When we fully opened the aperture of D06V1, the vertical emittance blow-up didn't occur up to ~1.5 mA/bunch.
  - (D06V1 aperture) close: ±2.9 mm, open: ±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.

Vertical Emittance w/wo BxB FB (Mar. 1st)

33-bunch operation

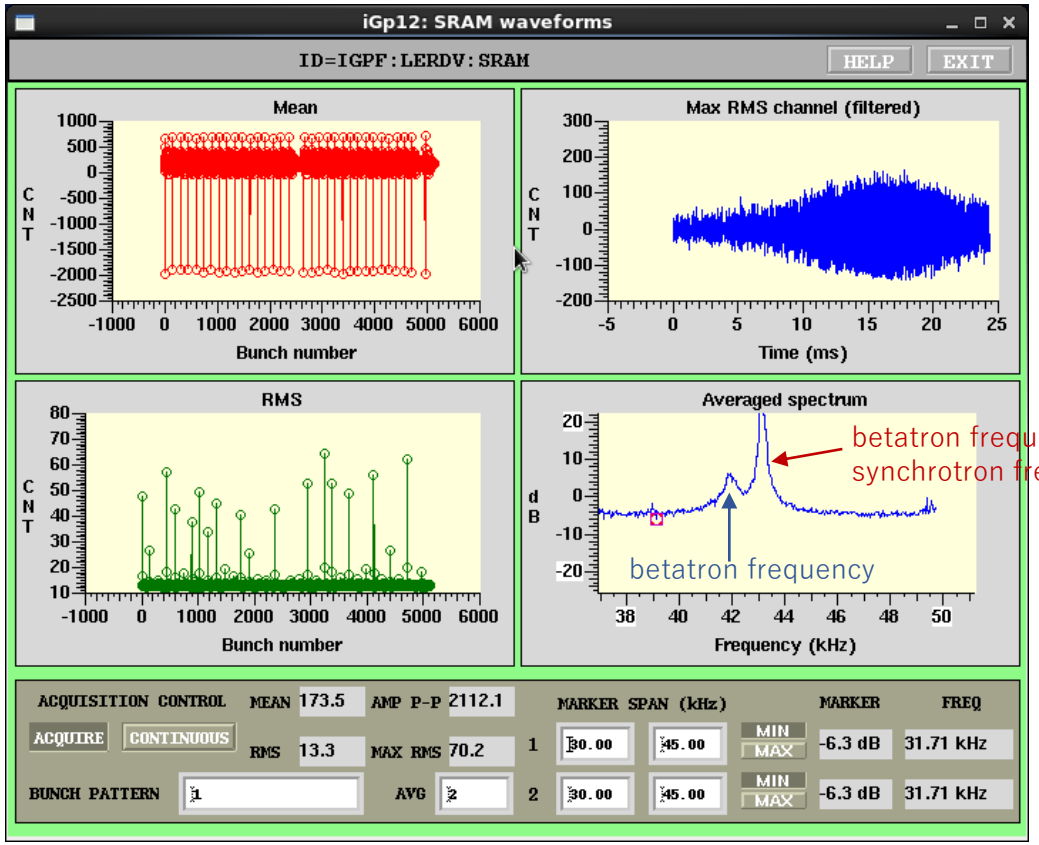




- We observed the vertical emittance with turning on/off the feedback (FB) with small number of the bunches to avoid multi-bunch instabilities.
- When we turned on the FB, the blow-up occurred around 0.85 mA/bunch.
- When we turned off the bunch-by-bunch FB, the vertical emittance blow-up didn't occur 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_β line (99.8-41 kHz) with resistive kick, but the FB becomes reactive for the f_β-f_s 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_β-f_s 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

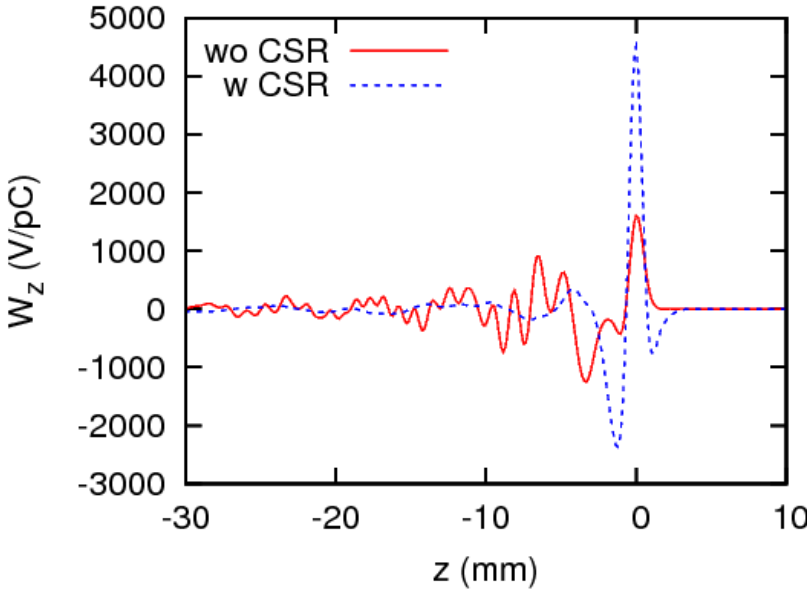
- Localized impedance at D6V1 is used.
- Beam size increases when -1 mode appears at ~0.9mA.
- The 0 and -1 modes are not coupled at the current. The threshold of TMCI is ~2mA.

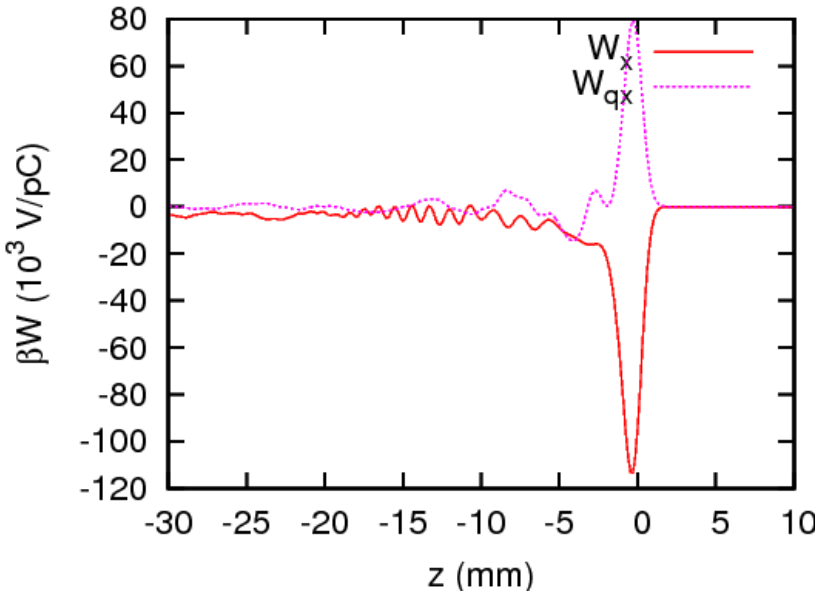
- Studies considering both the impedance and bunch-by-bunch feedback are necessary.

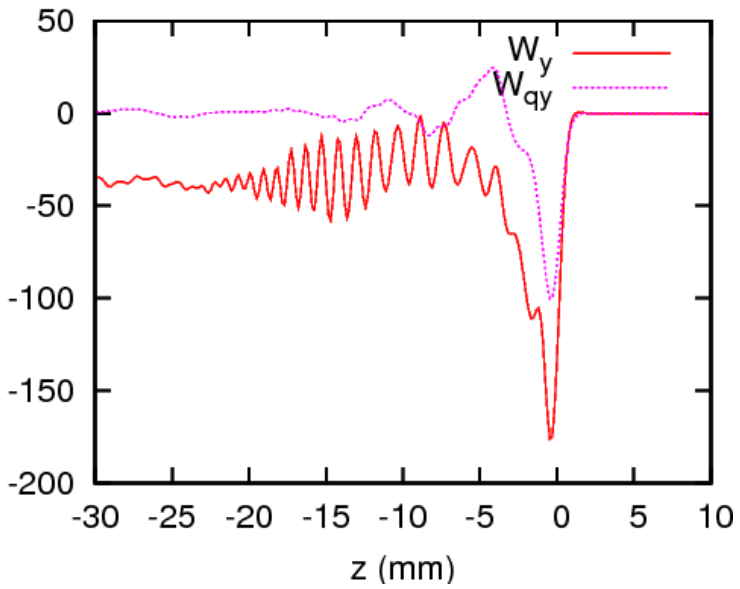
Wake force used in simulations (prepared by D. Zhou, T. Ishibashi)

- Wake field is calculated by ECHO3D (collimators), GDFidl (cavity and other vacuum components) and analytic (resistive wall).
- Kick Factor $\beta_y K_y$, $\beta_y K_{qy}$ (V/C)
  - $\beta_y K_y + \beta_y K_{qy}$ is -3.3×10^{16} V/C for collimators, and -1.8×10^{16} V/C for others. -5.1×10^{16} V/C for total.
  - Tune shift is $\Delta\nu_y = 0.01/mA$. The threshold of TMCI is around 2mA ($\nu_s = 0.023$)

$$\Delta\nu_\beta = 2.00\times10^{-19}\sum_i \beta_i K_{\perp i} I(mA)$$

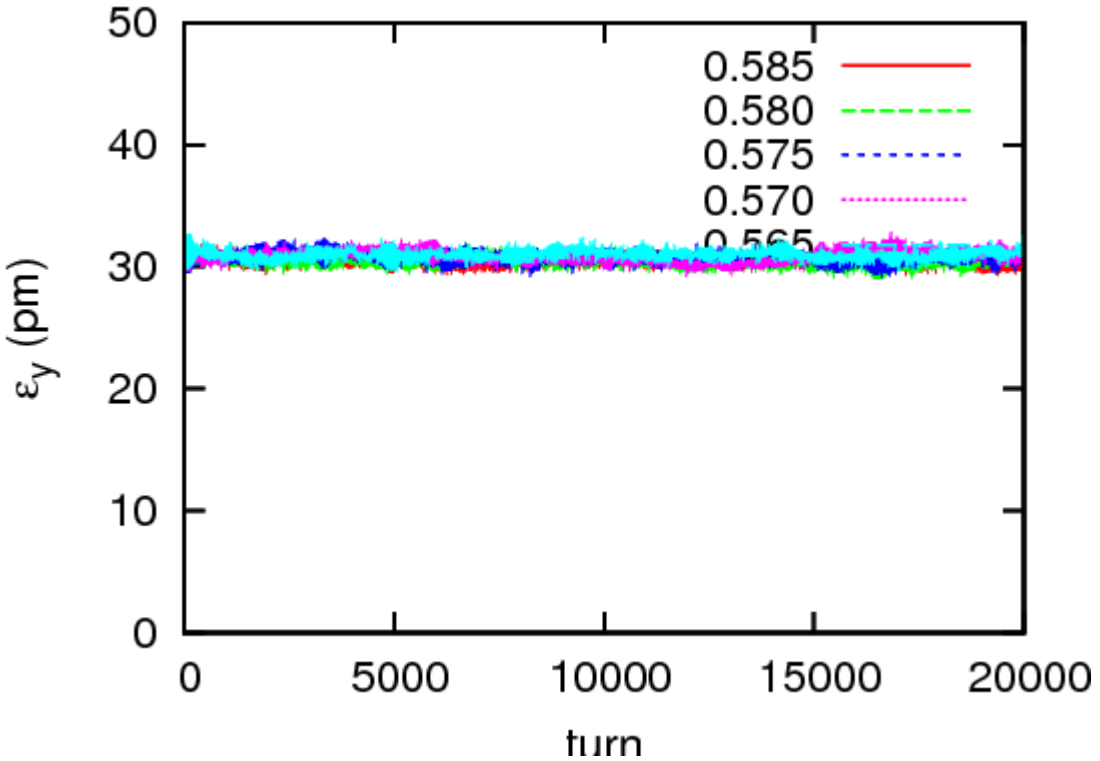




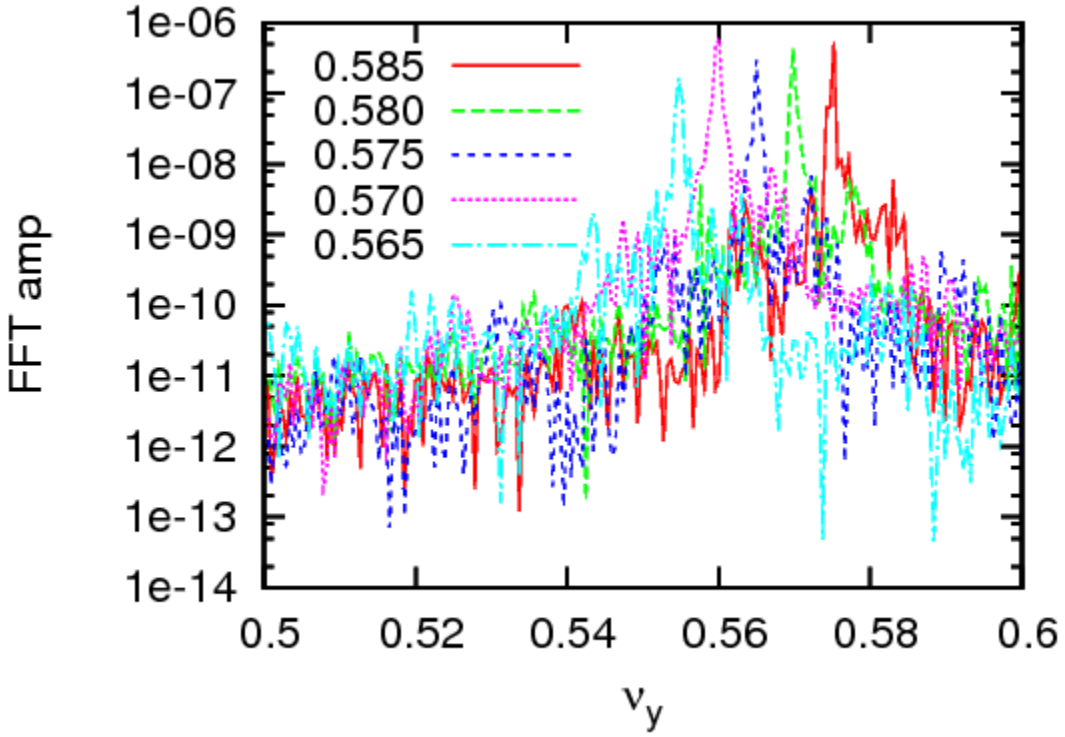


Simulation for the impedance

- I=1mA, $\Delta\nu_y$=0.01



0 mode is seen. Tune shift is 0.01/mA



- No emittance increase.

Mode analysis for simple BxB Feedback

- Resistive and reactive component of the feedback

$$\Delta p_y(J,\phi) = -2d_p\langle p_y\rangle - 2d_y\langle y\rangle \qquad \Delta p_y(J,\phi) = -2d_p\int p_y(J',\phi')\psi(J')dJ'd\phi' - 2d_y\int y(J',\phi')\psi(J')dJ'd\phi'$$

- The feedback works only in l=0 mode.

$$\begin{pmatrix} \bar{x}_l(J) \\ \bar{p}_l(J) \end{pmatrix} = M_{FB,l,J,l',J'} \begin{pmatrix} x_{l'}(J') \\ p_{l'}(J') \end{pmatrix} \qquad \psi(J) = \frac{1}{2\pi\varepsilon}e^{-J/\varepsilon}$$

$$M_{FB} = \begin{pmatrix} 1 & 0 \\ -4\pi d_y\delta_{l0}\delta_{l'0}\psi(J')\Delta J & 1-4\pi d_p\delta_{l0}\delta_{l'0}\psi(J')\Delta J \end{pmatrix}$$

- Considering betatron phase difference between the feedback kicker and the wake source

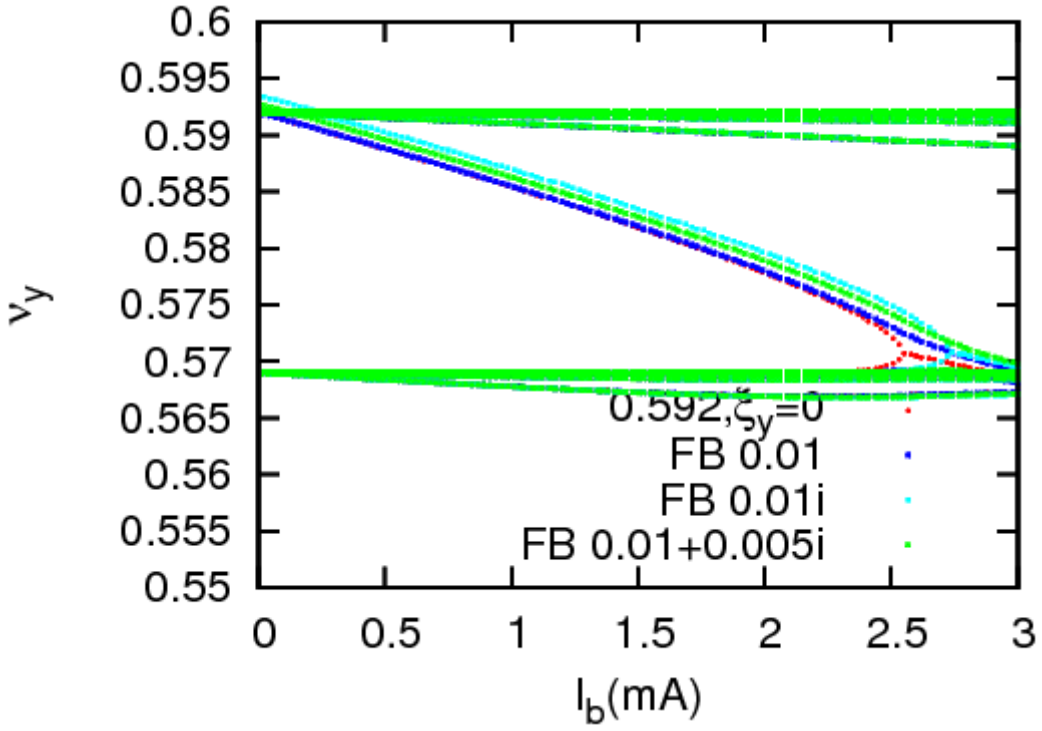
$$D_{p,y} \equiv 4\pi d_{p,y}\delta_{l0}\delta_{l'0}\psi(J')\Delta J$$

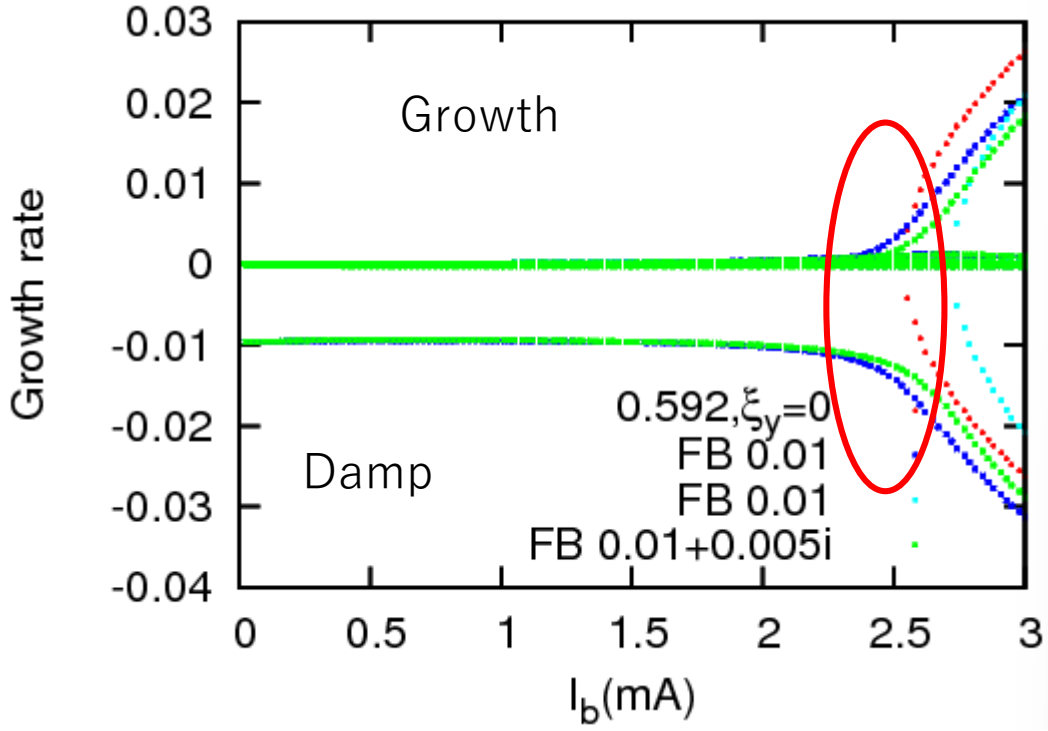
$$M^{-1}_{w\to FB}M_{FB}M_{w\to FB} \qquad M_{w\to FB} = \begin{pmatrix} \cos\phi_{w\to FB} & \sin\phi_{w\to FB} \\ -\sin\phi_{w\to FB} & \cos\phi_{w\to FB} \end{pmatrix}$$

$$M^{-1}_{w\to FB}M_{FB}M_{w\to FB} = \begin{pmatrix} 1-D_p\sin^2\phi + D_y\sin\phi\cos\phi & D_p\sin\phi\cos\phi + D_y\sin^2\phi \\ D_p\sin\phi\cos\phi - D_y\cos^2\phi & 1-D_p\cos^2\phi - D_y\sin\phi\cos\phi \end{pmatrix}$$

Mode analysis for zero chromaticity

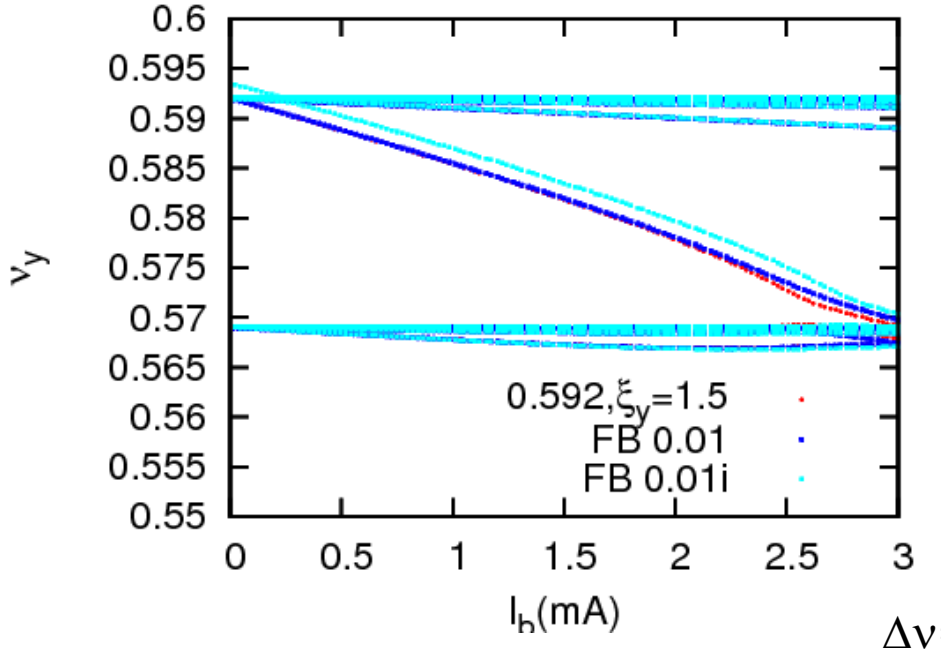
- At zero chromaticity, imaginary part of tune apprear blow the TMCI threshold as is demonstrated by E. Metral. $[M] \neq 1$
- The strength seems weak.

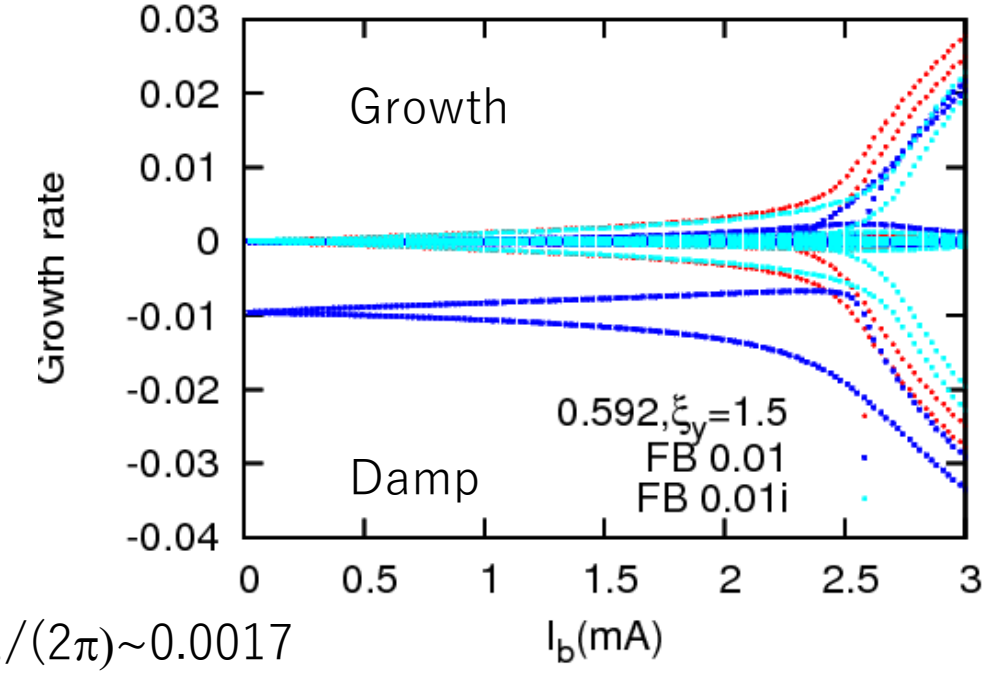




Mode analysis for ξ_y=1.5

- Effects of chromaticity is dominant compare with the resistive feedback.



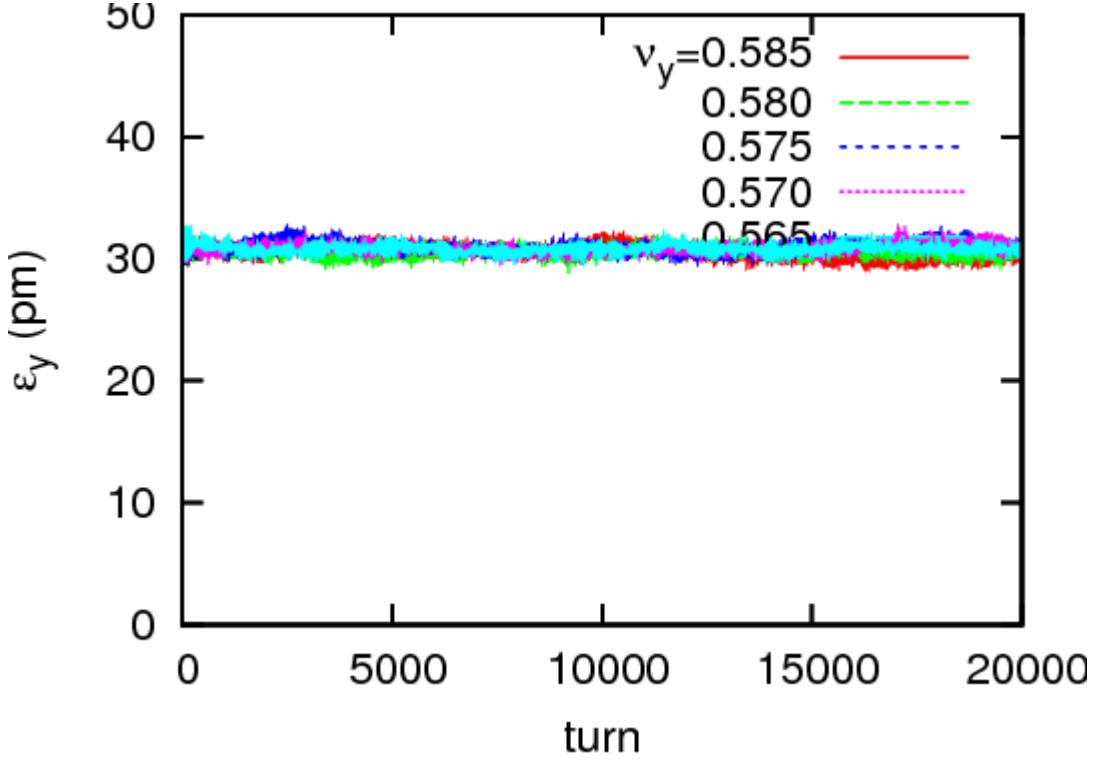


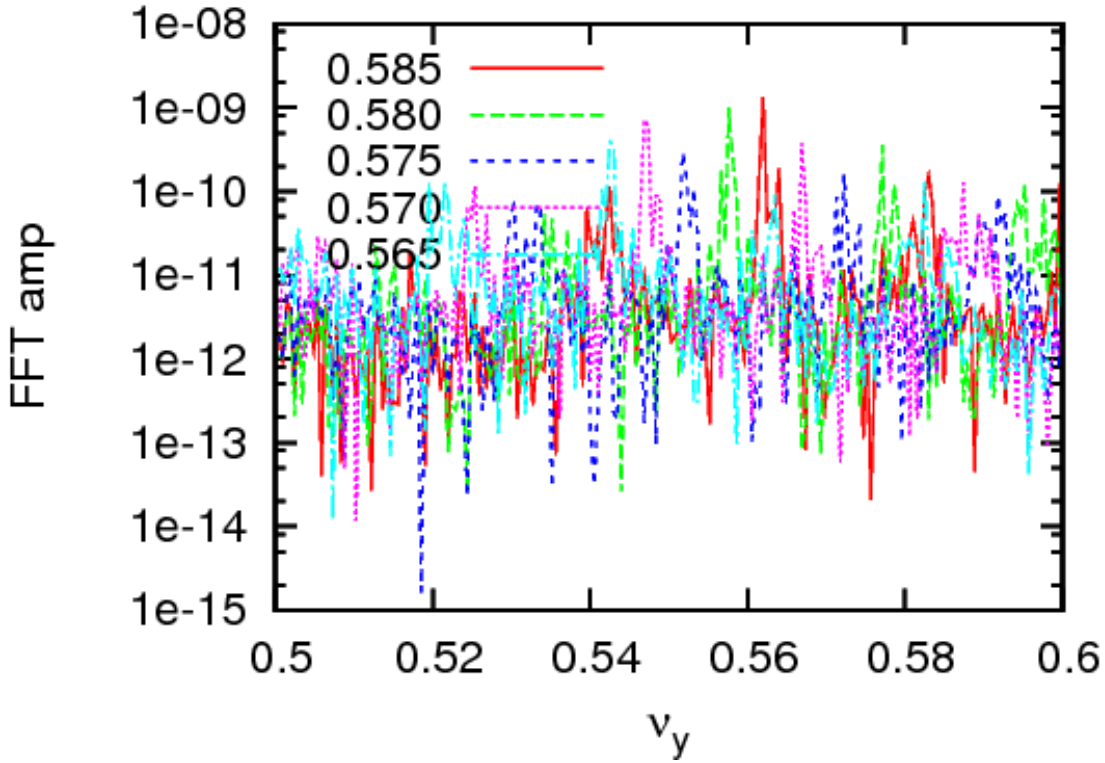
$\Delta\nu=0.01/(2\pi)\sim0.0017$

- Simulation using the simple FB system did not show the -1 mode instability (see next page).
- -1 mode instability can not be explained by the simple feedback system.

1 tap resistive feedback

- The simple feedback model
- Use 2nd feedback loop, FB gain 0.1. No growth at G=0.15.
- Choose ϕ(K2)= ϕ(M1)+0.25-ν_y(0.585).
- No emittance increase. -1 mode is seen.





Bunch by Bunch feedback system in SuperKEKB-LER

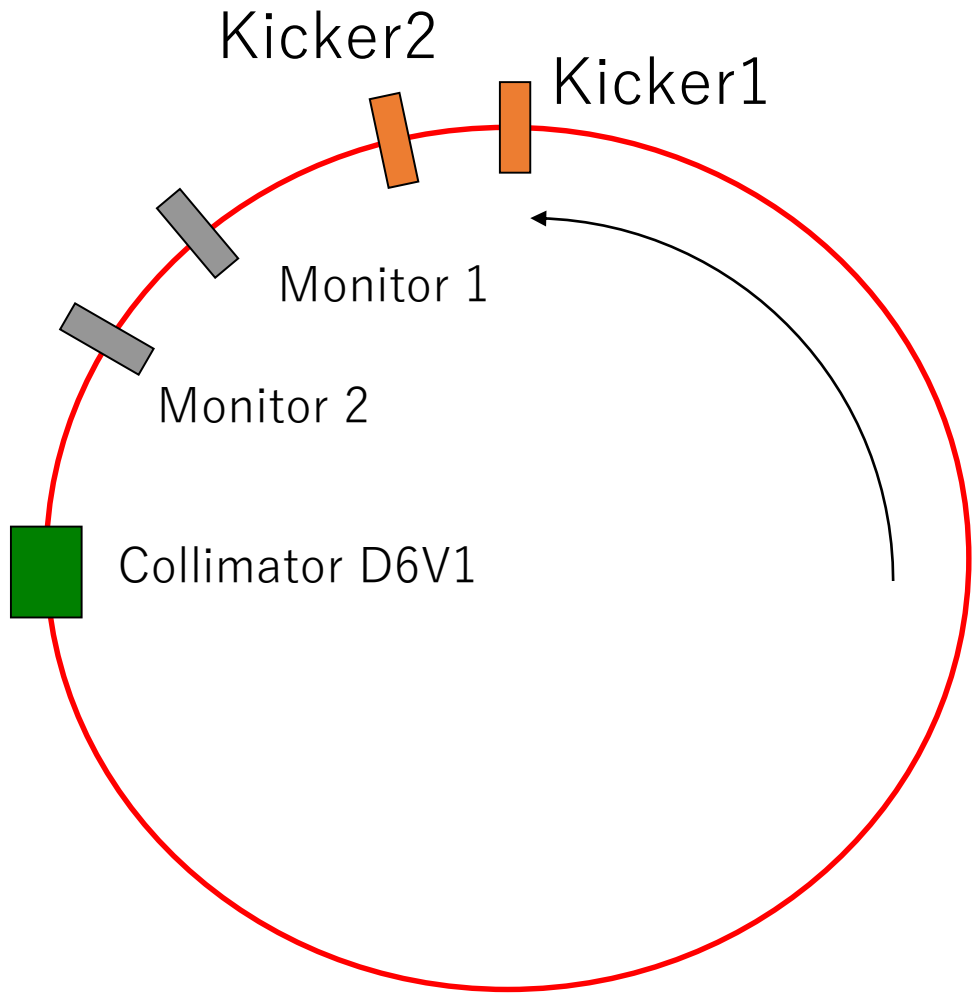
- 2 feed back loop working independently, TFBK1-FBMON1 and TFBK2-FBMON2
- Max 10 tap

AX	BX	NX	Element	Length	s(m)	AY	BY	NY	#	EX	EPX
.67792	19.5518	21.9781	PFZTFBK1	.00000	1489.30431	-1.1407	6.31089	22.7721	4006		
.69845	19.9303	21.9759	FZTFBKP1	.55000	1489.02931	-1.0404	5.71108	22.7648	4007		
.56341	17.6476	21.9913	PFZTFBK2	.00000	1490.83831	-1.7000	10.6686	22.8020	4009		
.58394	17.9631	21.9888	FZTFBKP2	.55000	1490.56331	-1.5997	9.76118	22.7977	4010		
.49527	23.9306	22.0432	PFBMON1	.00000	1499.90944	.84750	19.4097	22.9117	4034		
-.49527	23.9306	22.1906	PFBMON2	.00000	1519.05569	-.84750	19.4097	23.1355	4046		
-.60424	18.2863	22.2474	PFZLFBK1	.00000	1528.67382	1.50061	8.91787	23.2541	4070		
-.70726	20.0962	22.2588	PFZLFBK2	.00000	1530.05382	.99740	5.47061	23.2857	4073		
1.71319	14.6430	27.4756	PMD06V1	.00000	1870.26828	-10.133	67.3498	28.8574	4660	.516	-.0728
0.0000	.08000	44.5250	IP	.00000	3016.30649	0.0000	.00100	46.5870	8097		

model for SuperKEKB

- Betatron phase difference
- ϕ_y(M1)=22.9117, ϕ_y(K1)= 22.7721
- $\Delta\phi_y$(M1->K1)= 46.4474

- ϕ_y(M2)=23.1355, ϕ_y(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 $X_K(n)$, $P_K(n)$ are associated through the betatron motion with the tune $\mu=2\pi\nu$.

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

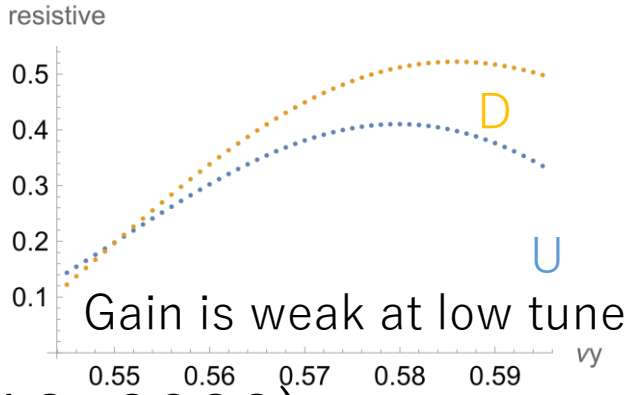
- Resistive and reactive components for FIR filter

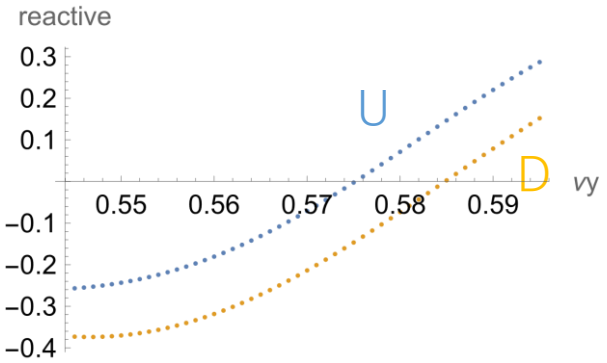
$$d_P = \frac{1}{2}\sum_{k=0}^{(N_{tap}-1)} c_{oef}(k)\sin(k\mu + \Delta\phi) \qquad d_X = -\frac{1}{2}\sum_{k=0}^{(N_{tap}-1)} c_{oef}(k)\cos(k\mu + \Delta\phi)$$

- 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.

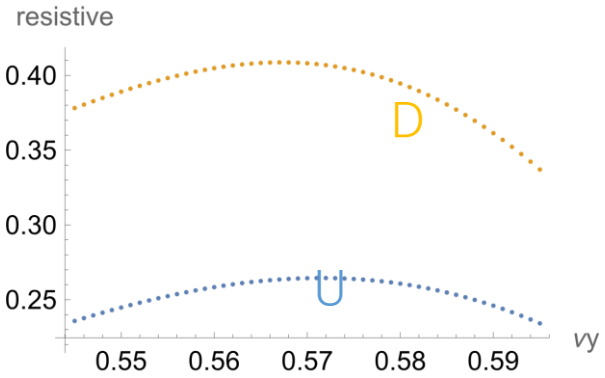
Resistive and reactive components

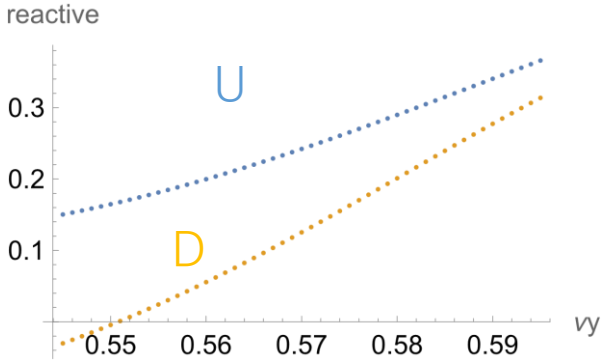
- Filter coefficients (~Mar. 11, 2022)
  - coef1={21623,-5530,-11430, 25925,-32767, 31362,-20832, 5288, 12317,-25956};
  - coef2={26781,-26182, 7149, 2479,-22777, 25564,-32767, 19752};





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





Simulation BxB feedback ON

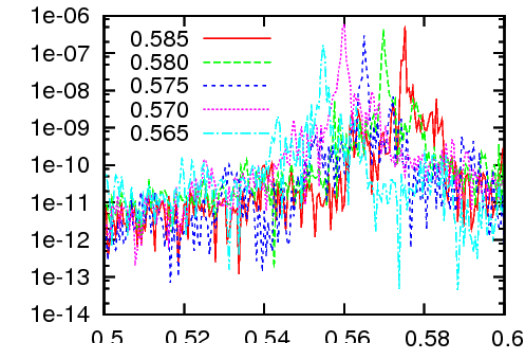
- The simulation considers the betatron phase phases of monitors, kickers and D6V1 collimator.

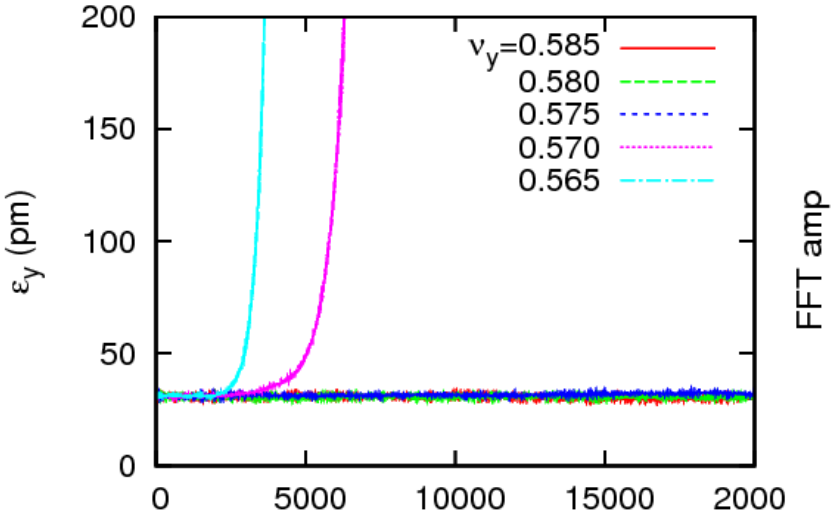
Vertical emittance and FFT y at 1mA/b

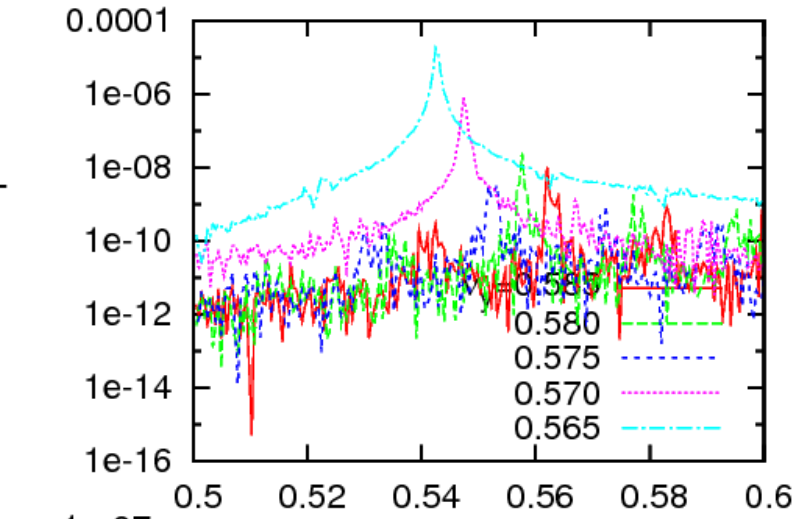
- First FBcoef (Mar. 11)

U D

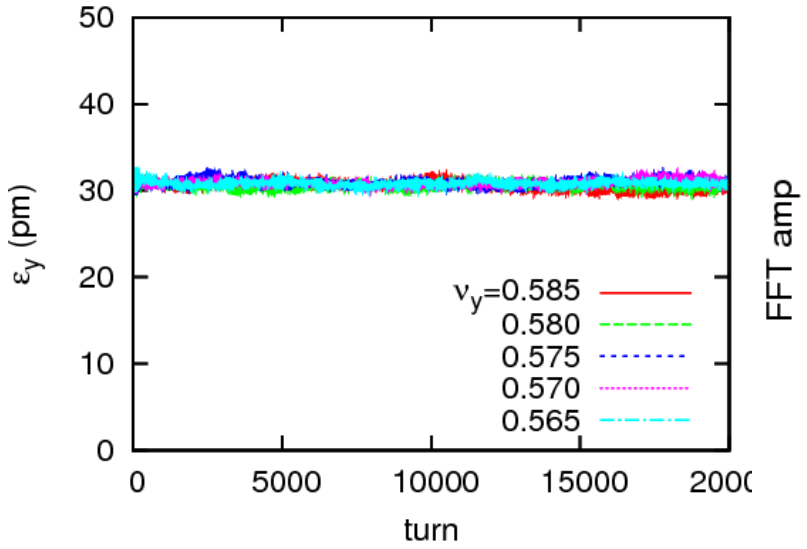
- G_{FB}=0.05+0.05

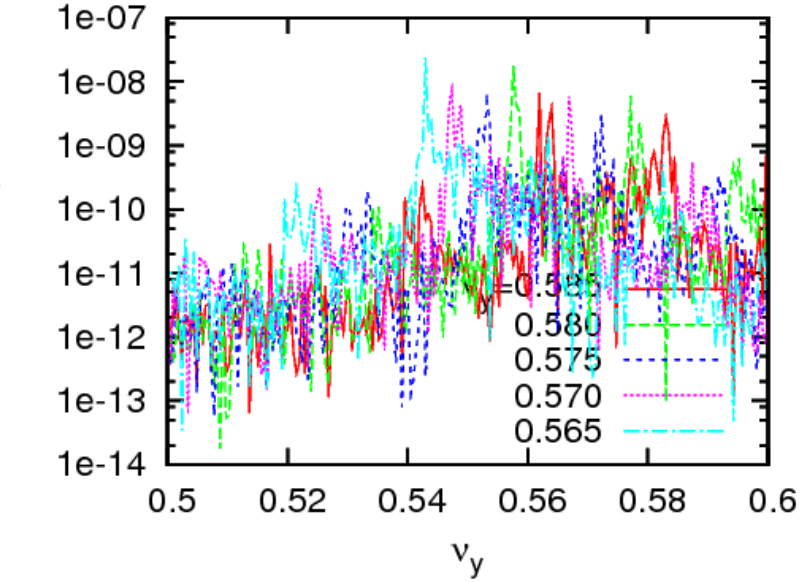






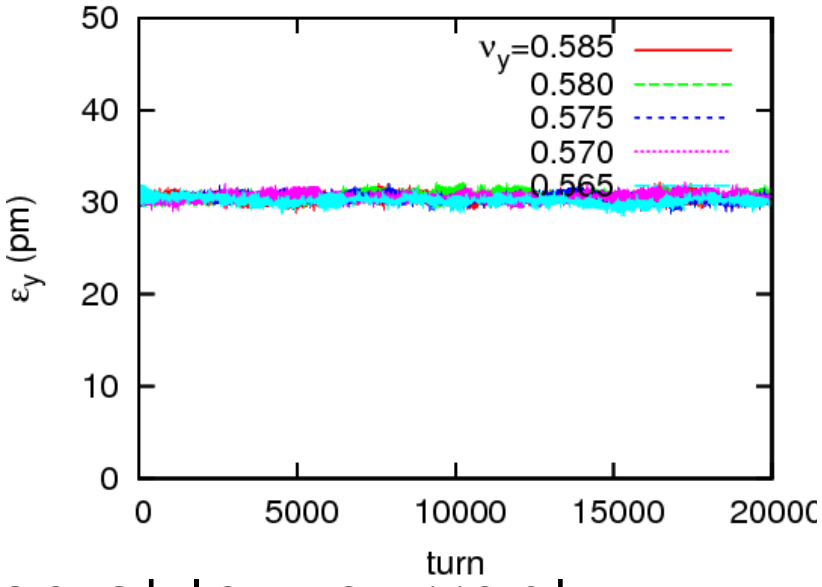
- G_{FB}=0.02+0.02

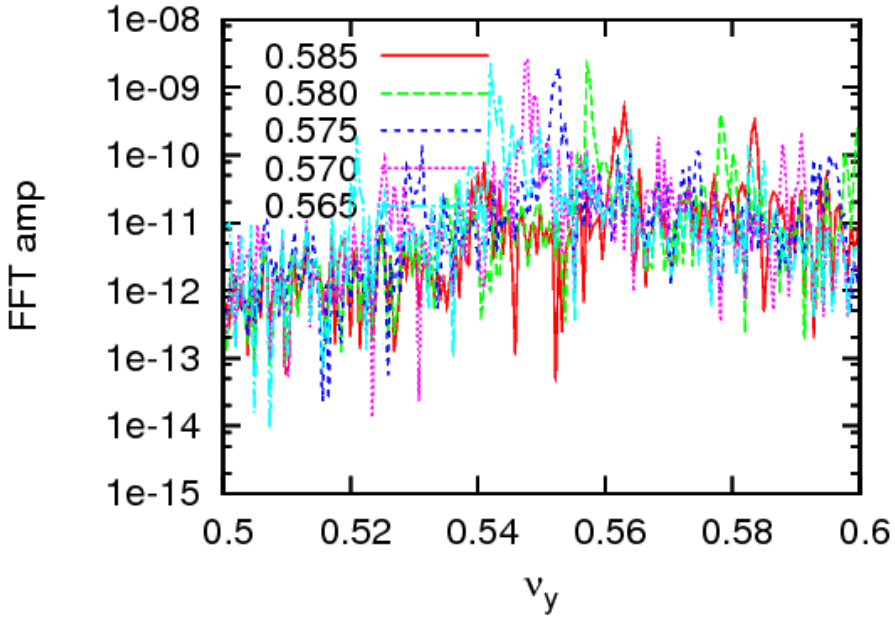




Vertical emittance and FFTy at I=0.5mA

- First FBcoef (Mar. 11)
- G_{FB}=0.05+0.05

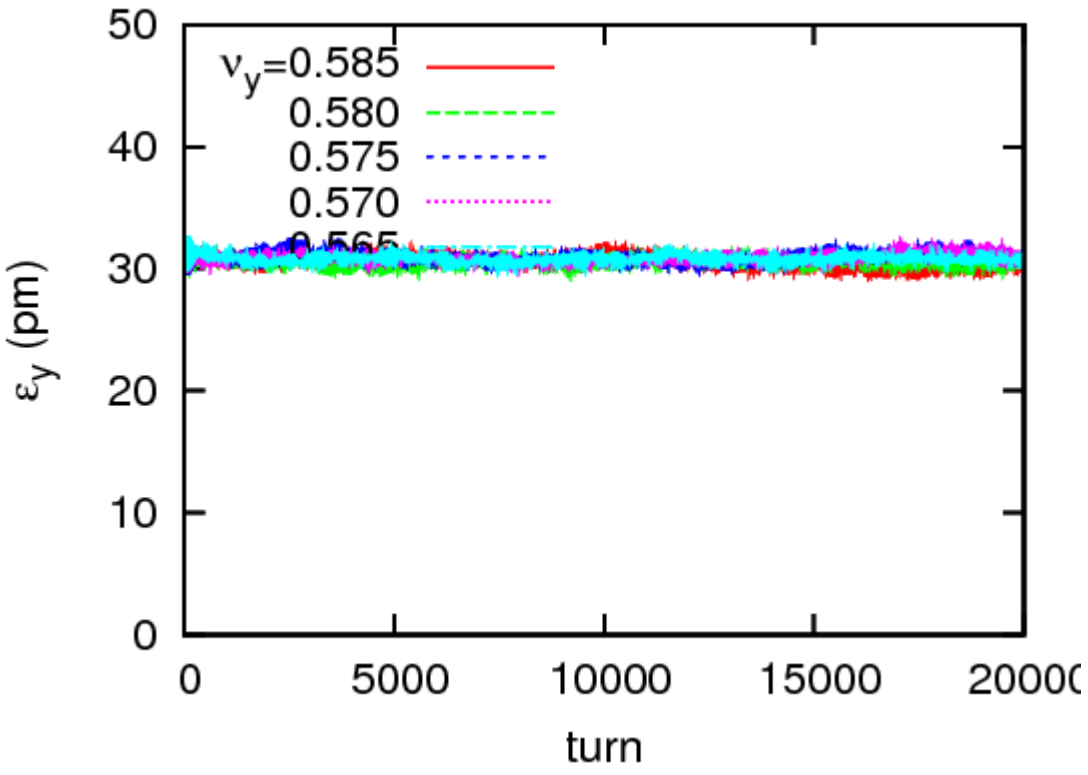


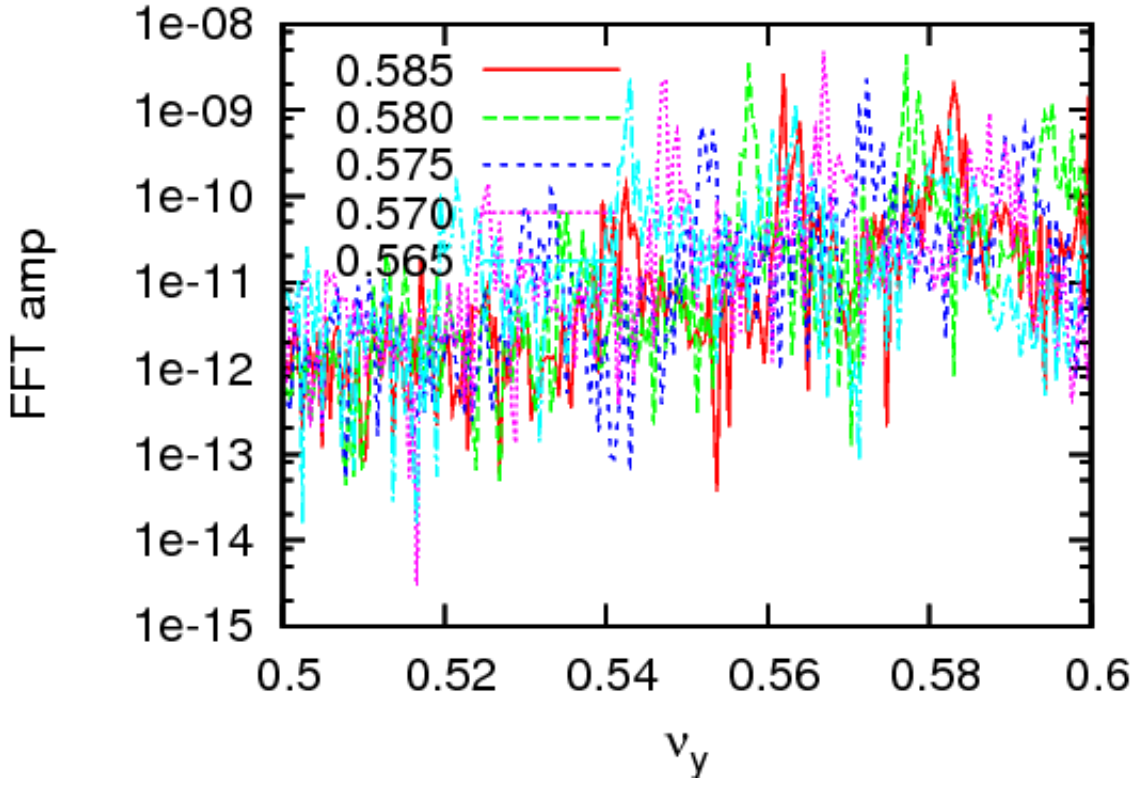


- No emittance increase at low current

Vertical emittance and FFT of <y>

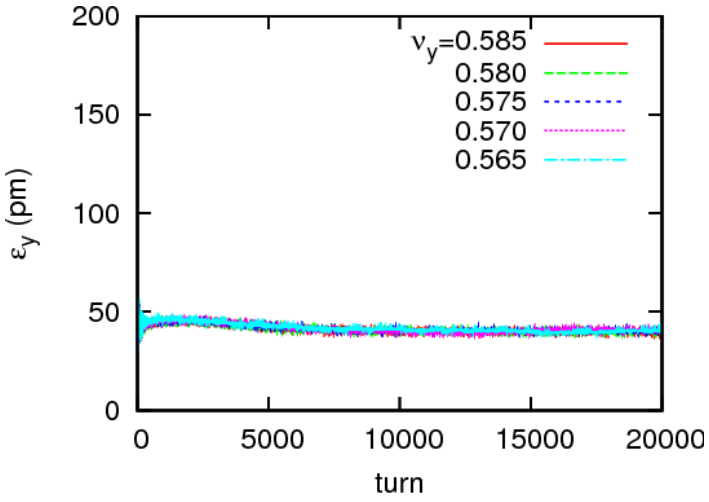
- Second FBcoef (Mar. 12)
- I=1mA/b
- Emittance increase at low ν_y is suppressed.

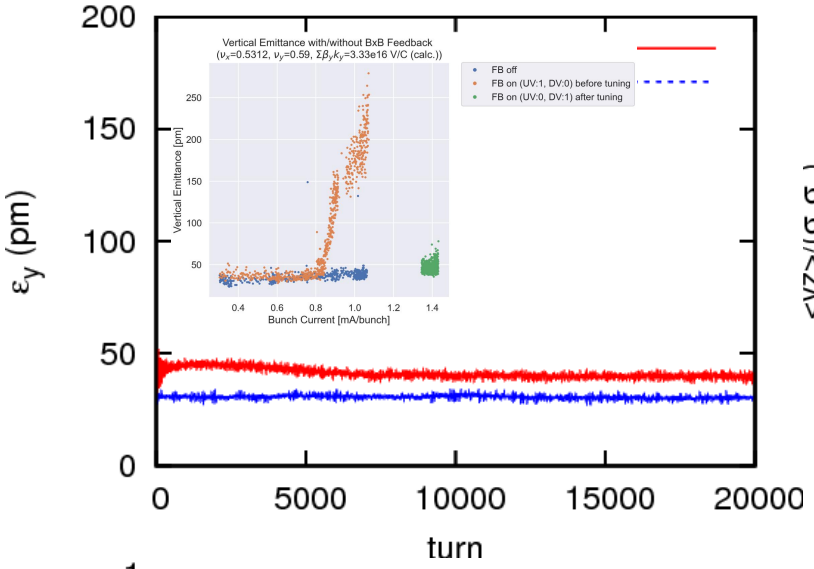


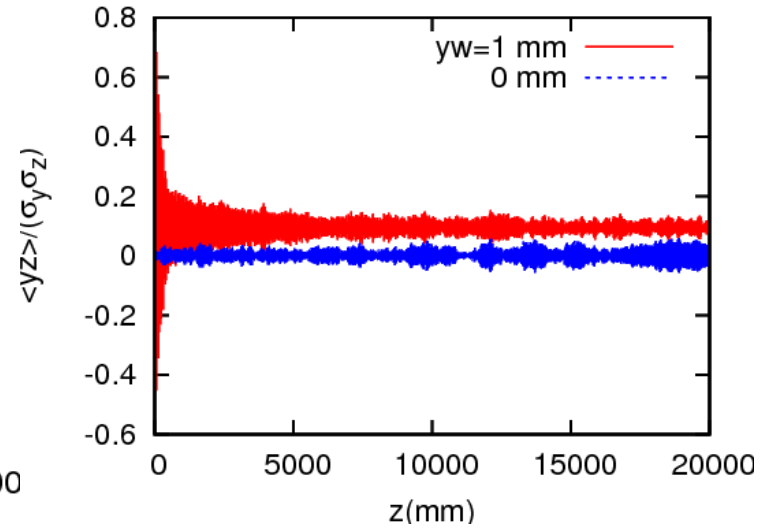


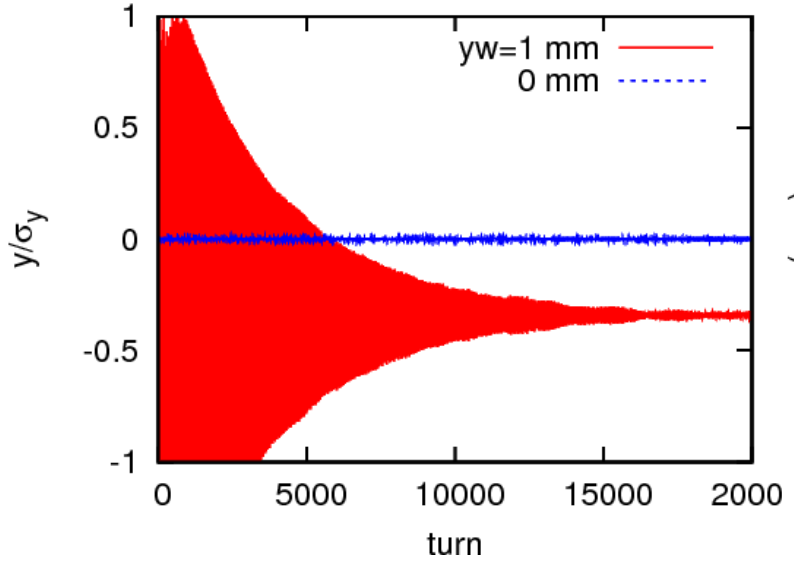
Effects of collimator offset – BxB FB OFF

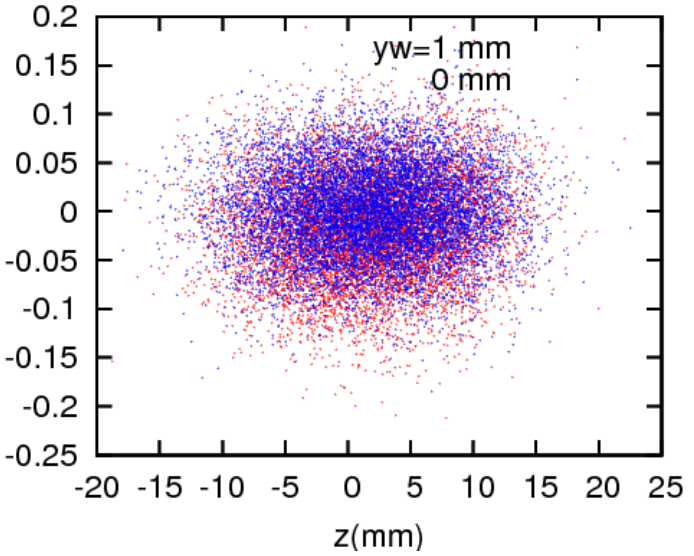
- Emittance increases 30->40pm at 1mA/b for collimator offset 1mm at D6V1.
- This may explain small emittance increase for the bunch current.
- Equilibrium orbit distortion as function of z. $\langle y \rangle = 0.3\sigma_y$, $\langle yz \rangle = 0.1\sigma_y\sigma_z$.
- No large emittance growth for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





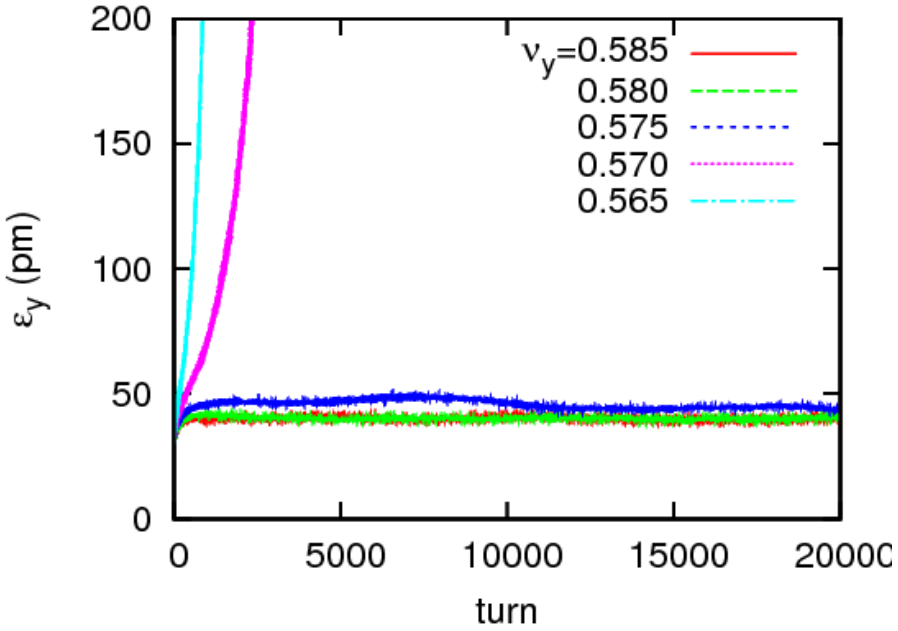


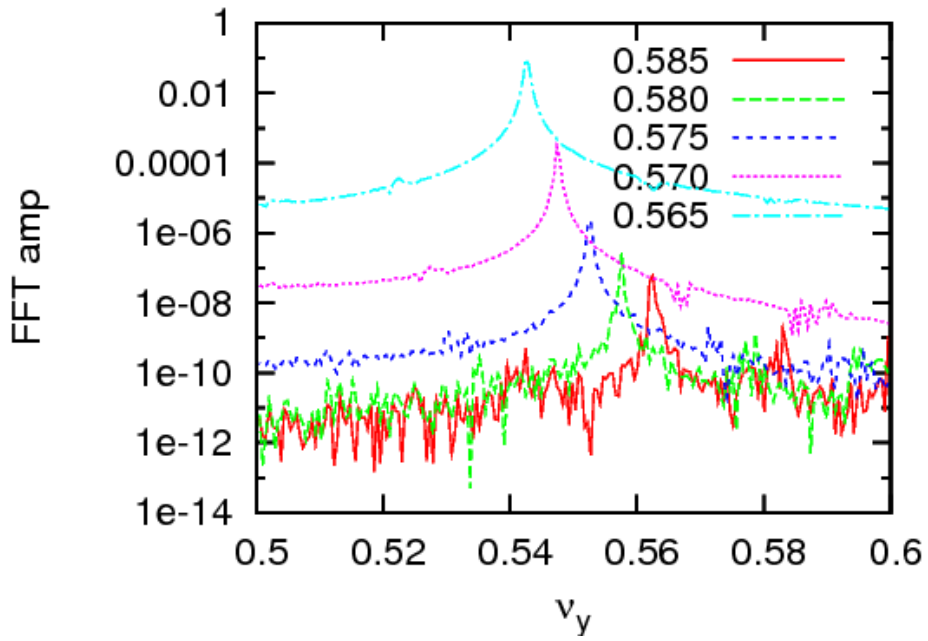




Effects of collimator offset – BxB FB ON

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

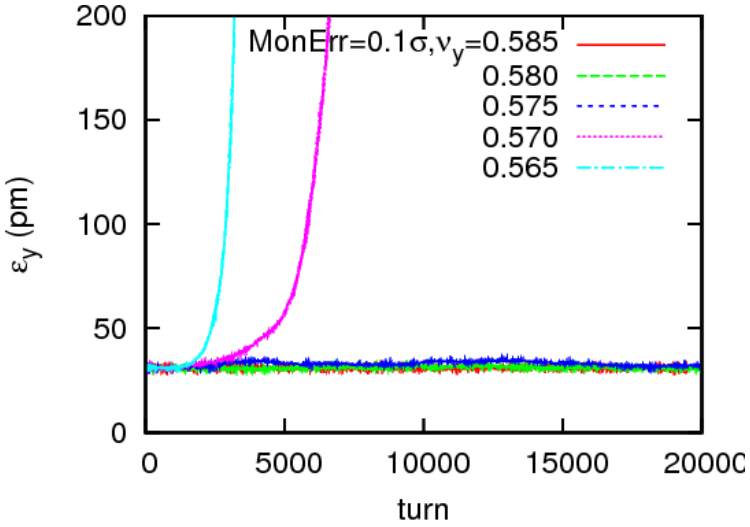


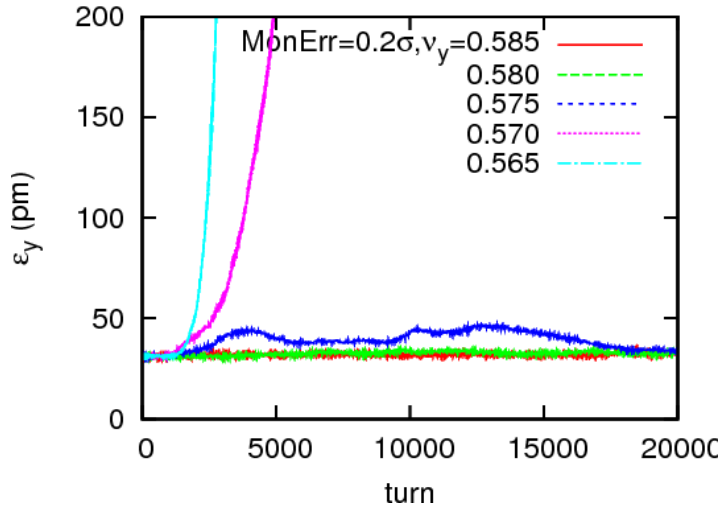


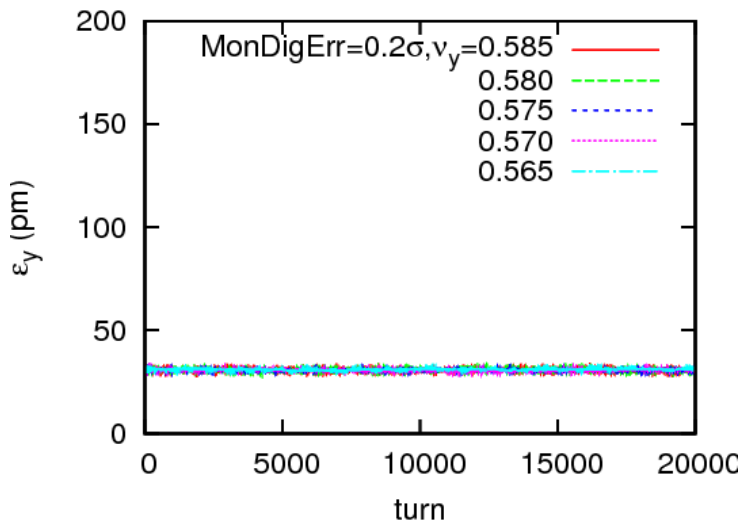
- No remarkable change from the case without collimator offset.

Monitor errors or digitized effects?

- Model with the monitor resolution and/or digitized 0.1-0.2σ_y.



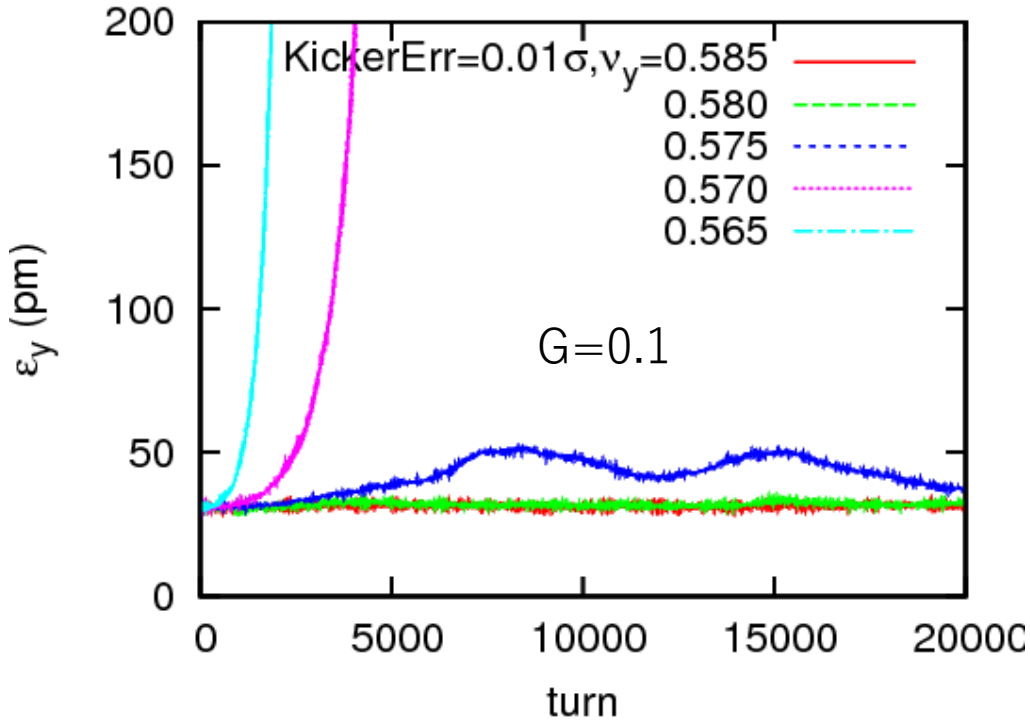




- No remarkable effect or suppression of instability was seen.
- -1 mode instability occurs at high FB damping rate 0.1 in the simulations at present.

Kicker noise

- Equilibrium power of the BxB feedback P=0.2 W, R=10kΩ.
- $P=V^2/R$, V~40 V. $\delta p_y/p_0 \sim 10^{-8}$. (M. Tobiyama)
- $\langle x' \rangle = (\varepsilon_y/\beta_y)^{1/2} \sim 1.7 \times 10^{-6}$.
- 1%σ_y noise is introduced in the simulation.



No remarkable change.
Slightly enhanced.
No instability at G~0.06.

Summary

- -1 mode instability, which is single beam and single bunch phenomenon, occurs high bunch current, narrow collimator aperture ($\Delta\nu_y$>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 -1 mode instability can be reproduced by simulation using transverse wake and high gain (G~0.1) multi-tap feedback.

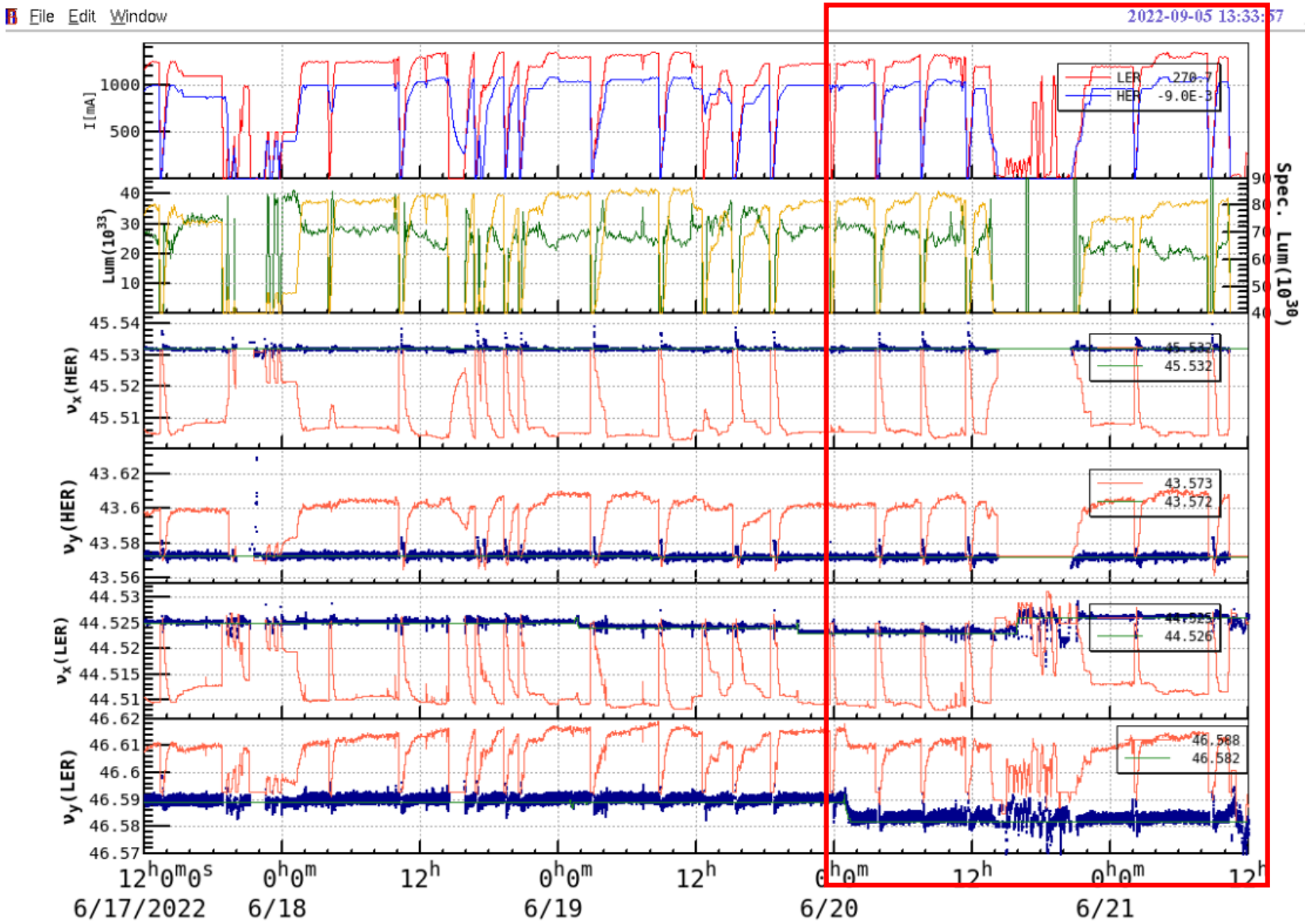
- Higher ν_y>0.58 is preferred for the instability, but injection is worse in the high vertical tune.
- This instability sometimes causes troubles in the physics operation due to condition of feedback and collimator and careless tune change.

Thank you for your attention

Summary for feedback

- Multitap (1st coef) and high gain feedback system (G=0.1) cause -1 mode instability.
- Multitap FB with 2nd 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, see later.



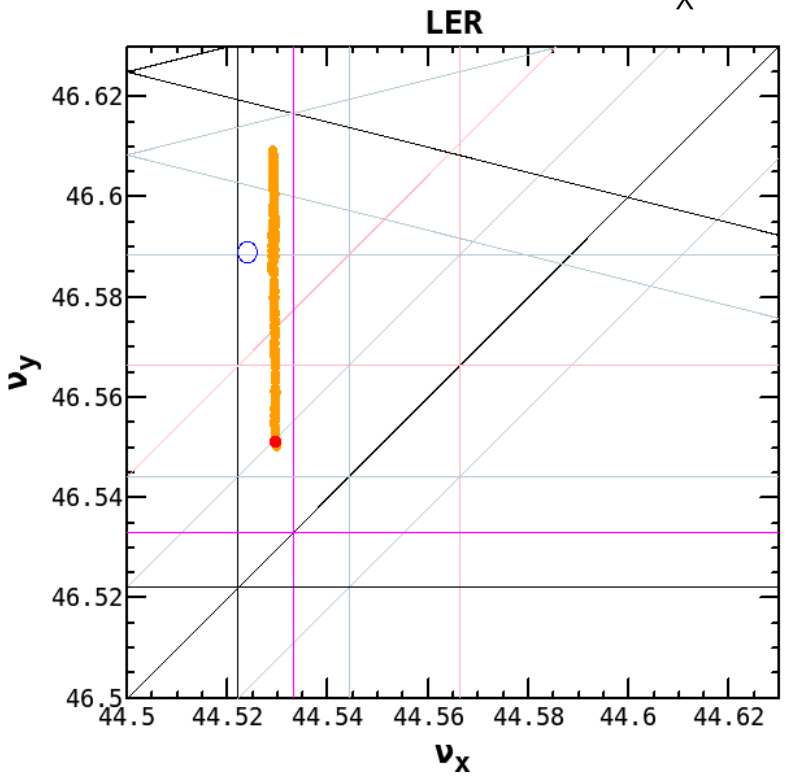
- Collision condition becomes worse when V tune go down carelessly.

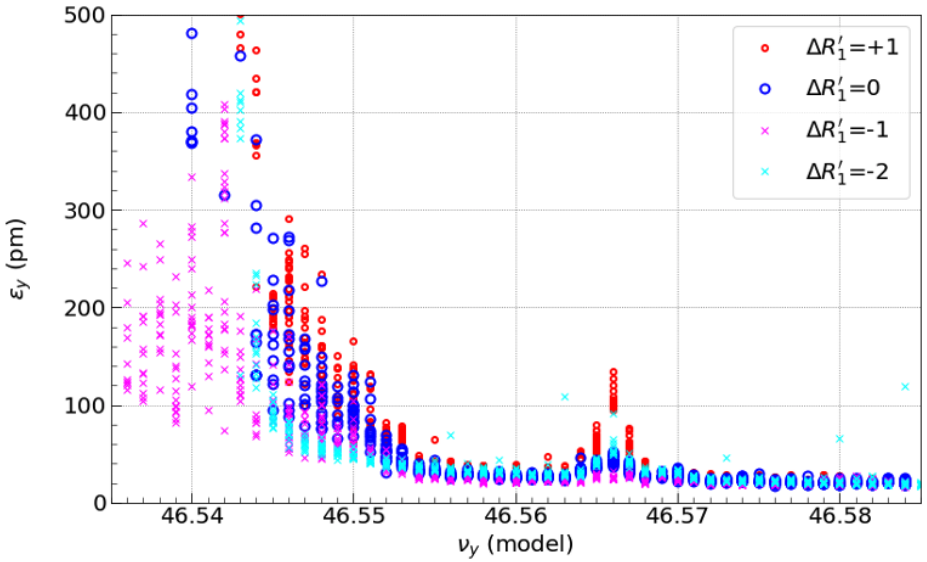
Vertical Beam size vs ν_y at by*=1mm (Dec. 2021)

No collision

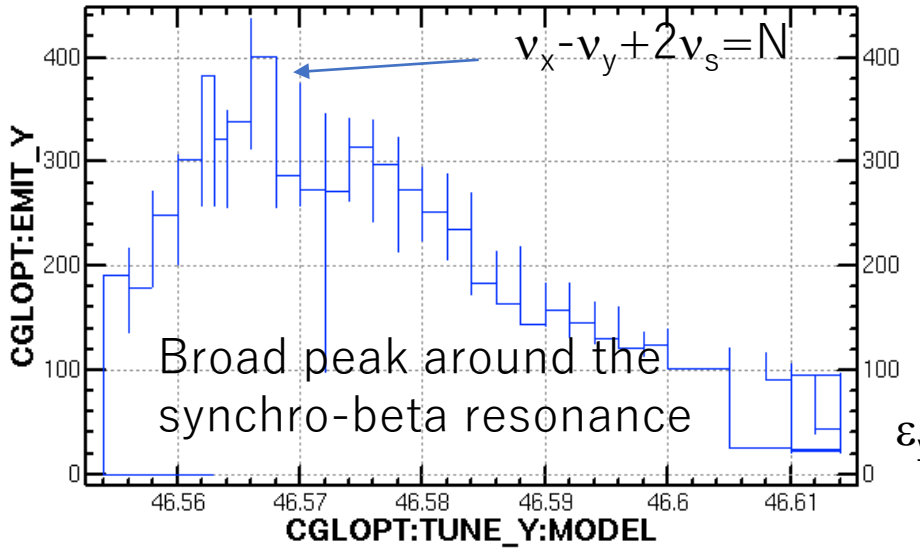
$k\beta=36.1\times10^{15}$ V/C

$\nu_x=0.529$





I=0.10mA/b

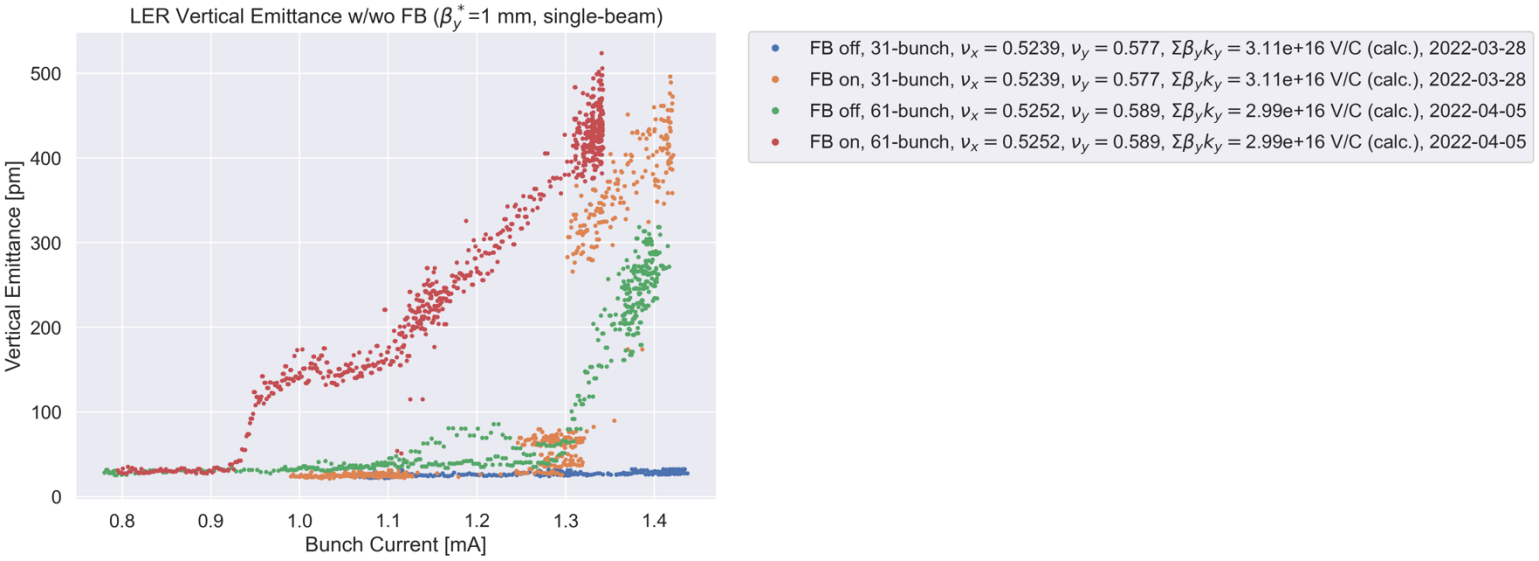


I=0.90mA/b

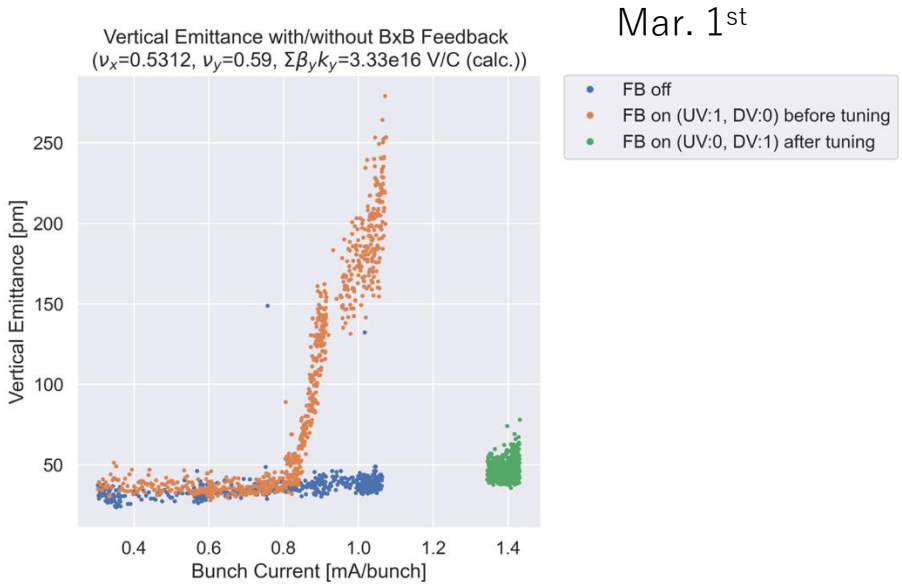
$\varepsilon_y\sim20$pm@$\nu_y=0.61$

Vertical Emittance w/wo FB (Mar. 28, Apr. 5)

- In this study, two FB loops were tuned to suppress f_β line, but the number of taps was reduced so that they didn't became reactive on f_β-f_s line.
- When we turned off the FB on Mar. 28th, we were able to accumulate up to ~1.45 mA/bunch for 31-bunch.
- When we turned on the FB on Mar. 28th, the threshold of the -1 mode instability was increased to ~1.3 mA/bunch for 31-bunch.
  - ✓ It was ~0.8 mA/bunch on Mar. 1st.
- When we turned off the FB on April. 5th, the threshold was ~1.3 mA/bunch 61-bunch (derived from multi-bunch instability?).
- When we turned on the FB on April. 5th, the threshold was ~0.95 mA/bunch 61-bunch.



Mar. 1st



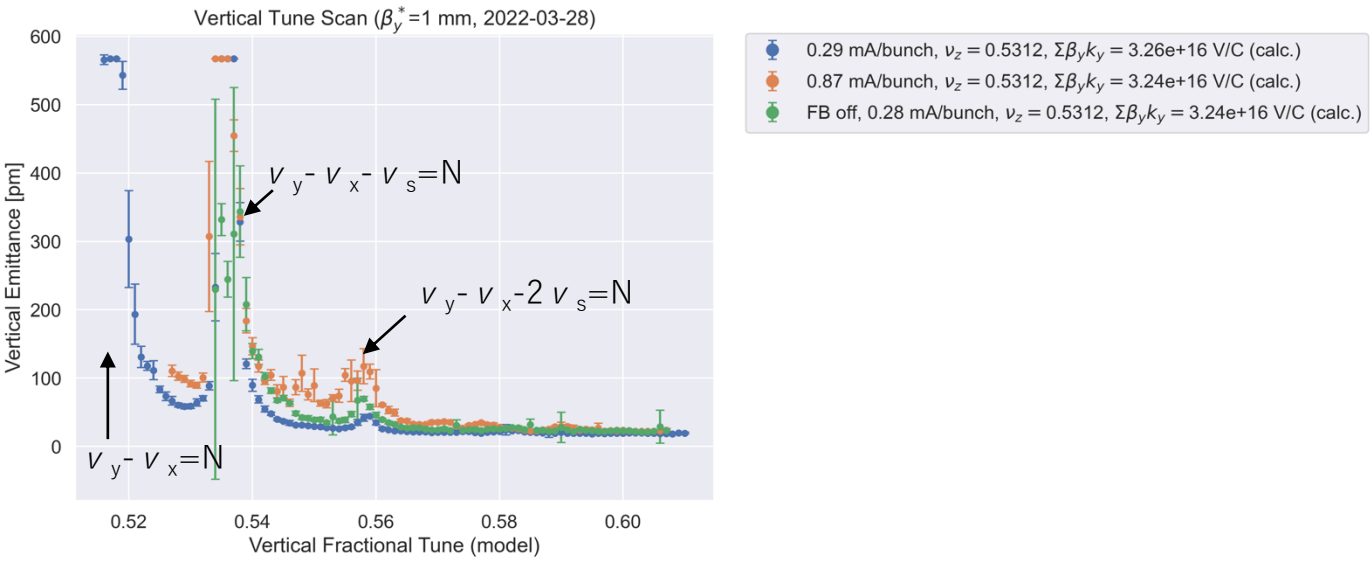
✓ Two FB loops were tuned to suppress the betatron frequency and the number of taps was reduced.

✓ In the green dots, one of them was tuned to suppress a frequency around (betatron – synchrotron).

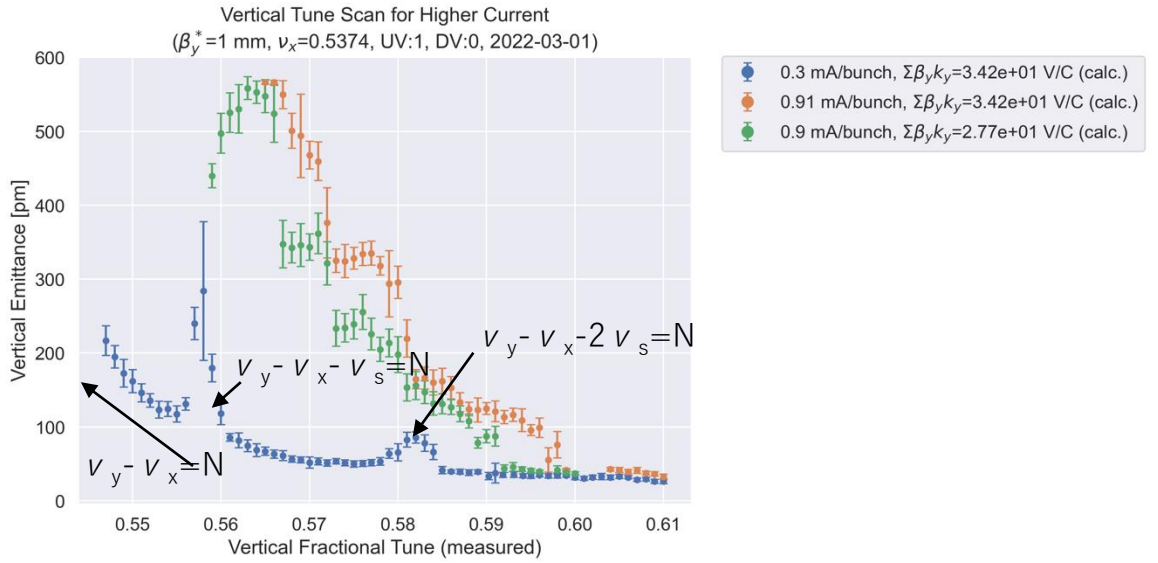
Tune Survey

- We scanned the vertical tune again after a tuning of the vertical bunch-by-bunch FB.
  - In this survey, two FB loops were tuned to suppress the betatron frequency.
  - The number of taps was reduced so that it would not be reactive as much as possible for a frequency around (betatron – synchrotron).
- The vertical emittance blow-up didn't occur around 0.9 mA/bunch on Mar. 28th.
- When we compare the lower bunch currents (~0.3 mA/bunch) w/wo the FB on Mar. 28th, it slightly suppresses the vertical emittance in some regions for the vertical tune.

2022-03-28 (31-bunch)



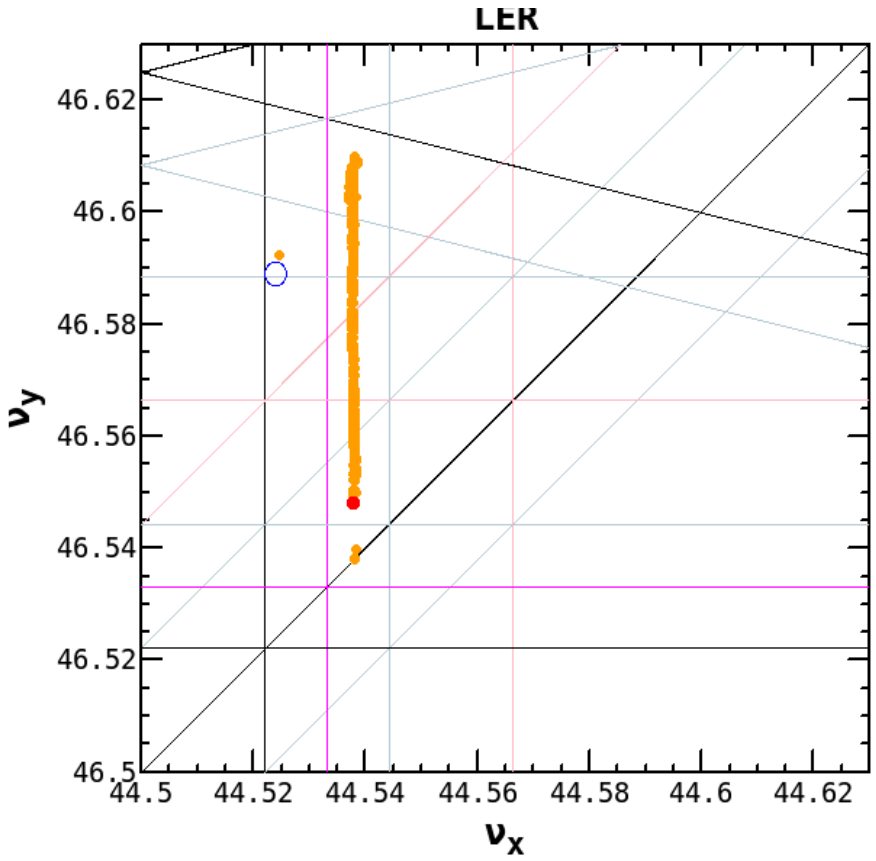
2022-03-01 (97-bunch)



Vertical Beam size vs ν_y at ν_x =0.538

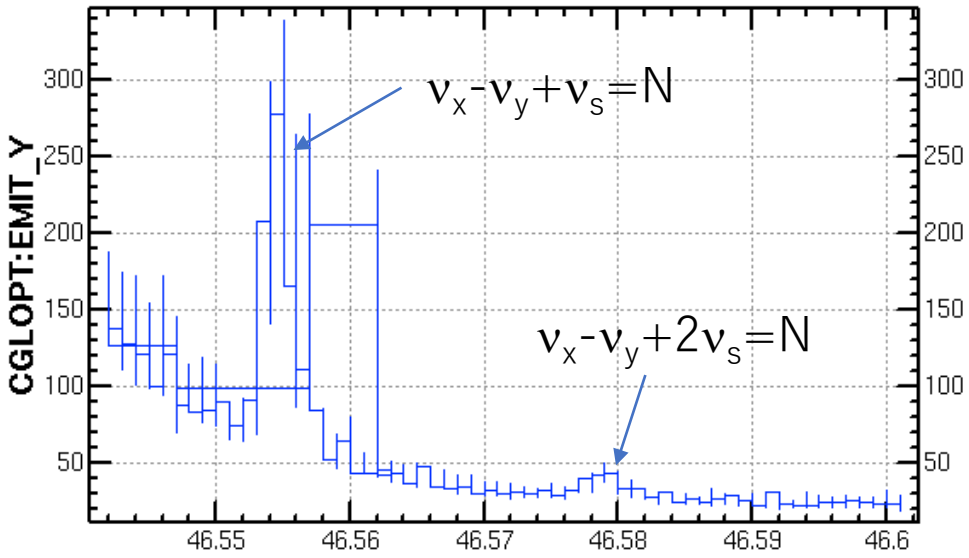
No collision

kβ=36.1x10^{15} V/C

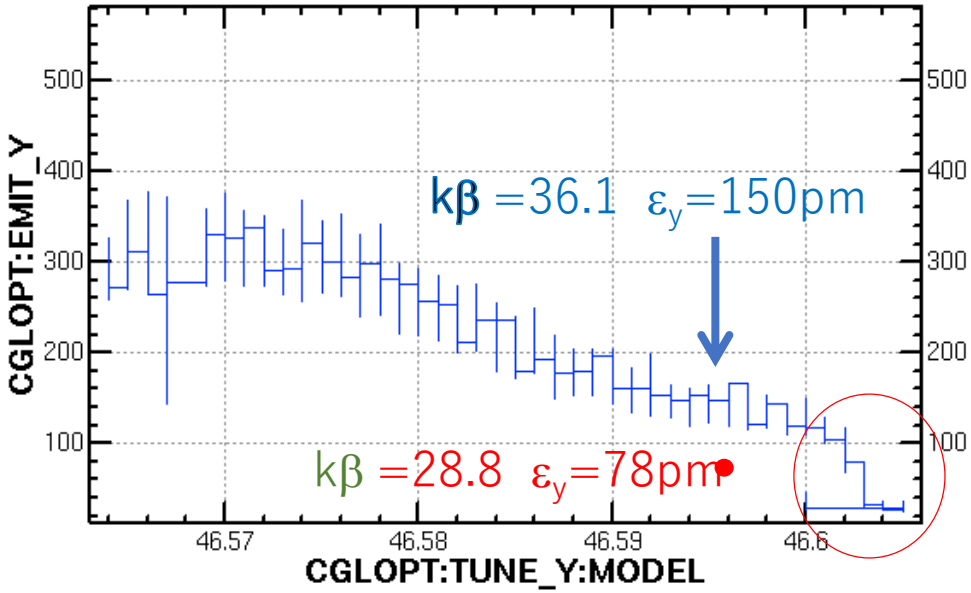


V Emittance depends on the impedance.

No $2\nu_y-m\nu_s=N$



I=0.30mA/b



I=0.90mA/b

Injection difficult 0.7mA/b at ν_y=0.6

Feedback system for a naive idea

- Betatron oscillation, $(X+iP)_n=e^{-in\mu}(X+iP)_0$ $\quad X=\frac{y}{\sqrt{\beta_y}}$ $\quad P=\frac{\alpha_y y+\beta_y y'}{\sqrt{\beta_y}}$
  1. Position data of Tap number is measured.
  2. Fourier amplitude and phase at a timing are determined. $(X+iP)_M=A\exp(-i\phi_M)$
  3. Phase at Kicker $\phi_K=\phi_M+\Delta\phi$. Betatron coordinate at kicker $(X+iP)_K=A\exp(-i\,\phi_K)$
  4. Kick the beam proportional to P_K(resistive) or X_K(reactive), $\Delta P=-2aP_K-2bX_K$

$$A\exp(-i\phi_M)=\frac{1}{N}\sum_{n=0}^{N-1}(X+iP)_n\exp(-in\mu)\approx\frac{2}{N_{tap}}\sum_{n=0}^{(N_{tap}-1)}X_n\exp(-in\mu)$$

$$(X+iP)_K=A\exp(-i\phi_M-i\Delta\phi)\approx\frac{2}{N_{tap}}\sum_{n=0}^{(N_{tap}-1)}X_n\exp(-in\mu-i\Delta\phi)$$

Pure resistive feedback

$$P_K=-\frac{2}{N_{tap}}\sum_{n=0}^{(N_{tap}-1)}X_n\sin(n\mu+\Delta\phi)$$

$$\Delta P=-2aP_K$$

Reactive feedback component

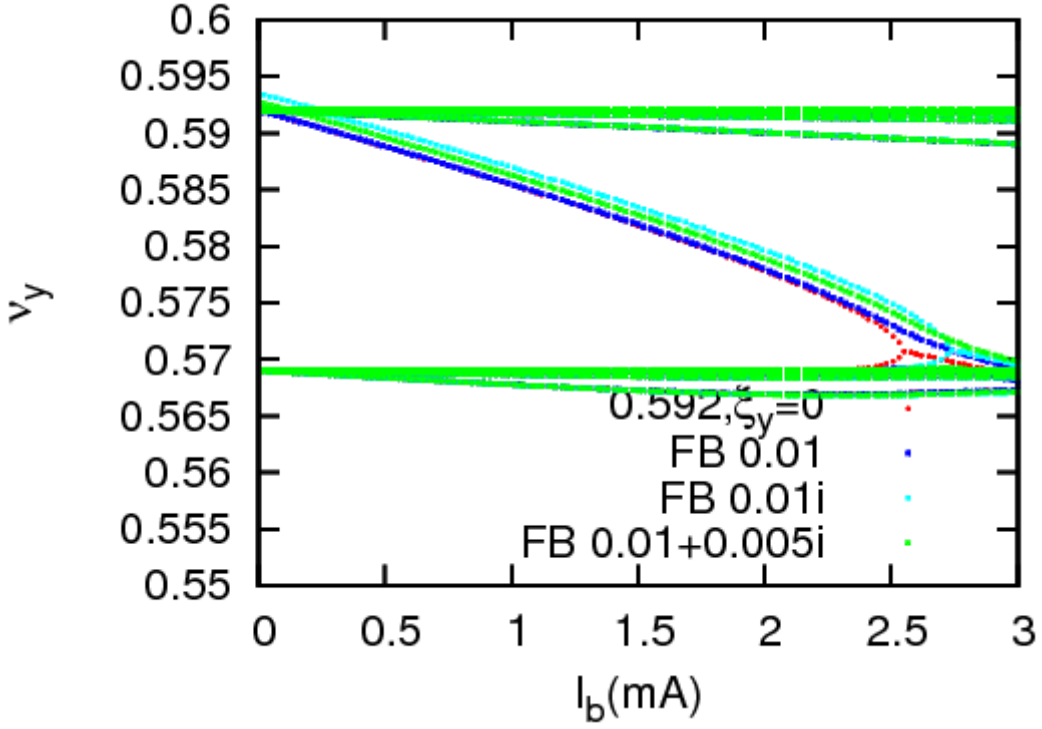
$$X_K=\frac{2}{N_{tap}}\sum_{n=0}^{(N_{tap}-1)}X_n\cos(n\mu+\Delta\phi)$$

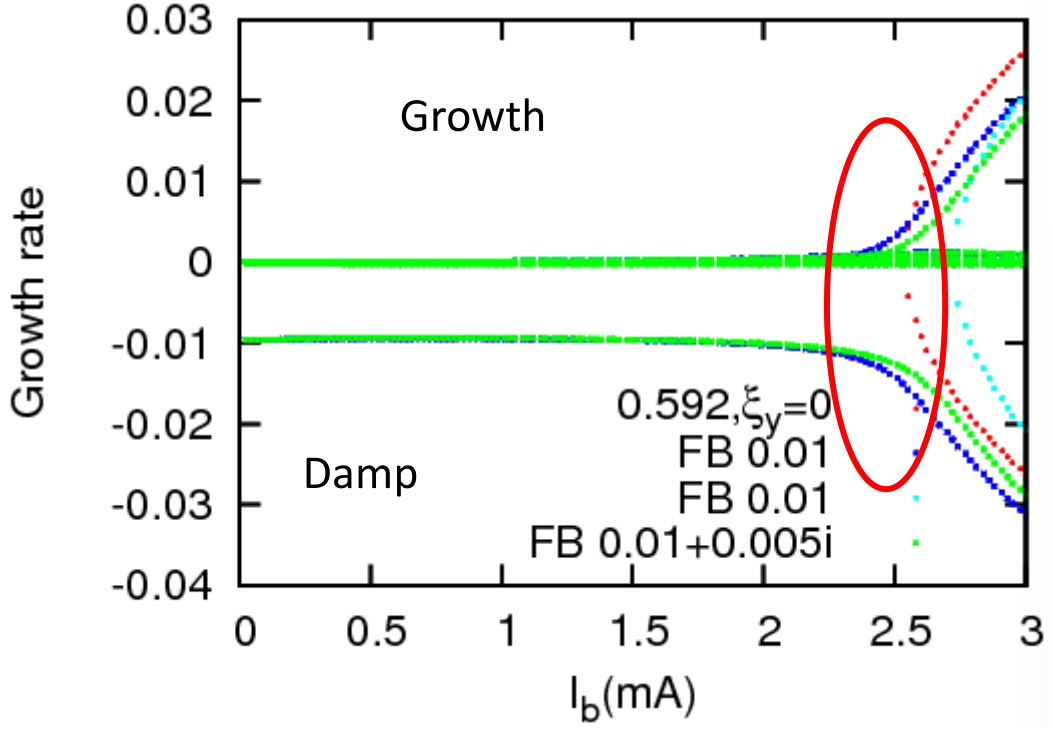
$$\Delta P=-2bX_K$$

[K. Ohmi]

Mode analysis for zero chromaticity

- At zero chromaticity, imaginary part of tune apprear blow the TMCI threshold as is demonstrated by E. Metral.
- The strength seems weak.

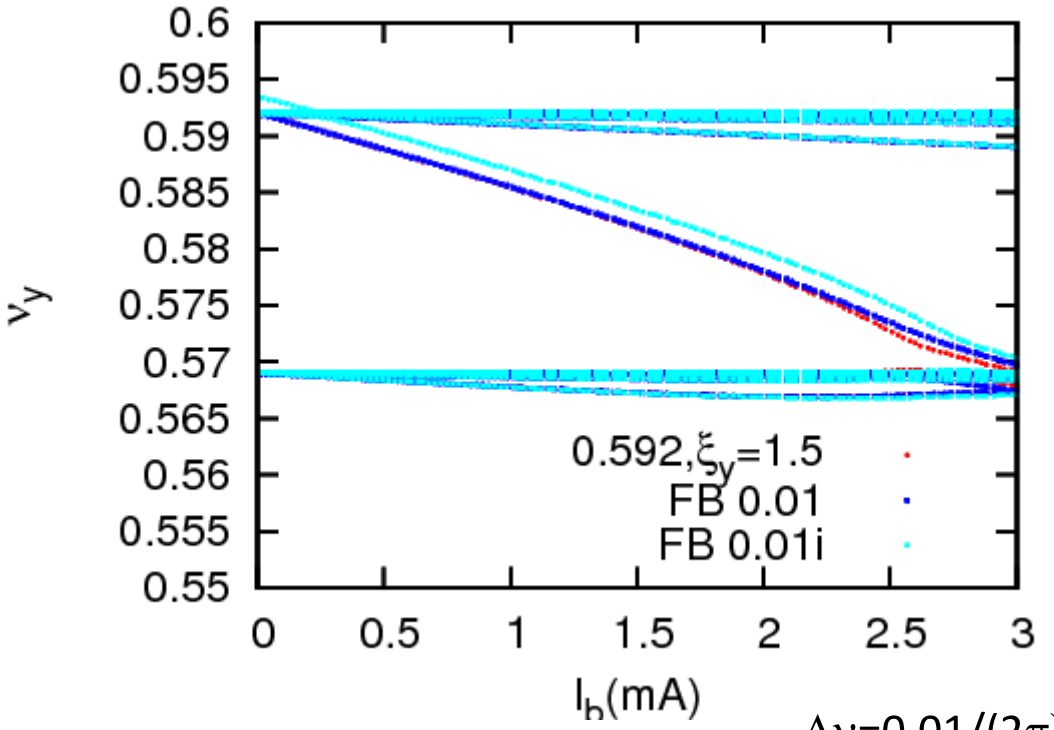




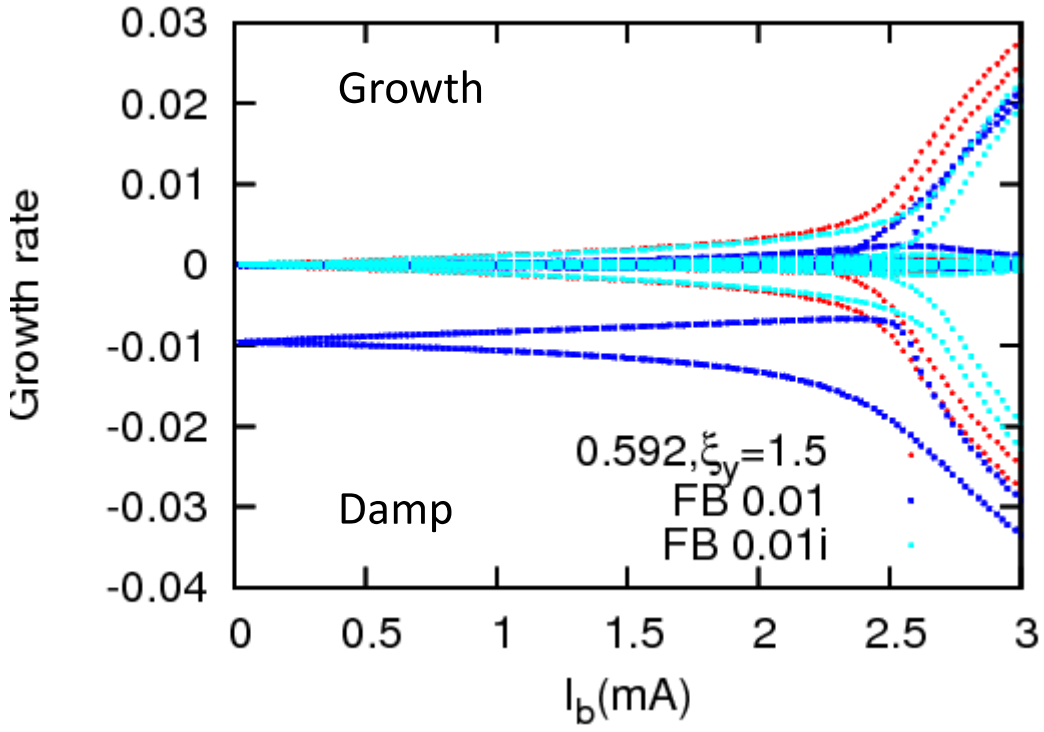
[K. Ohmi]

Mode analysis for ξ_y=1.5

- Effects of chromaticity is dominant compare with the resistive feedback.



$\Delta\nu$=0.01/(2π)~0.0017



[K. Ohmi]

Bunch oscillation mode affected by BxB feedback

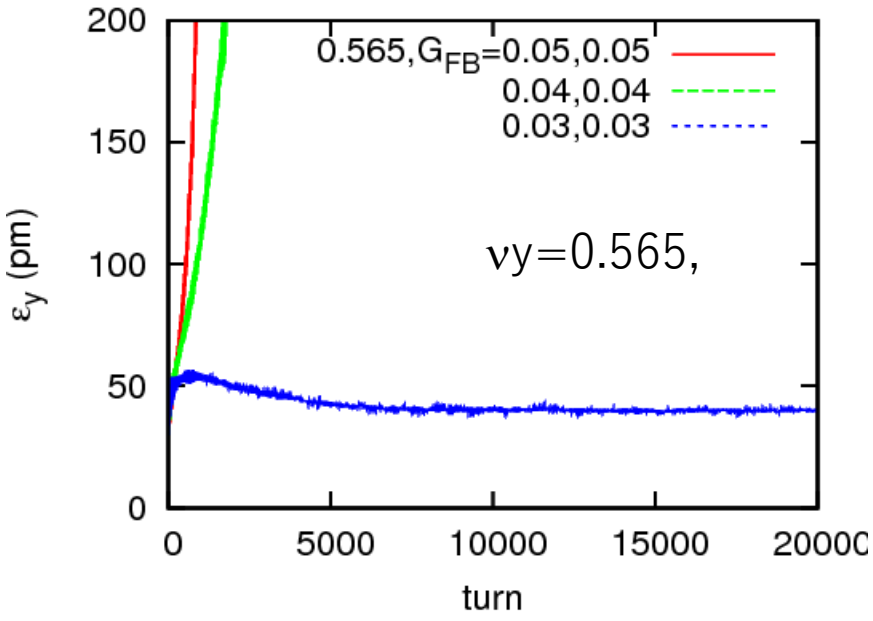
- E. Metral, Phys. Rev. AB 24, 041003 (2021)
  - Resistive feedback induced imaginary part (growth) in -1 mode.

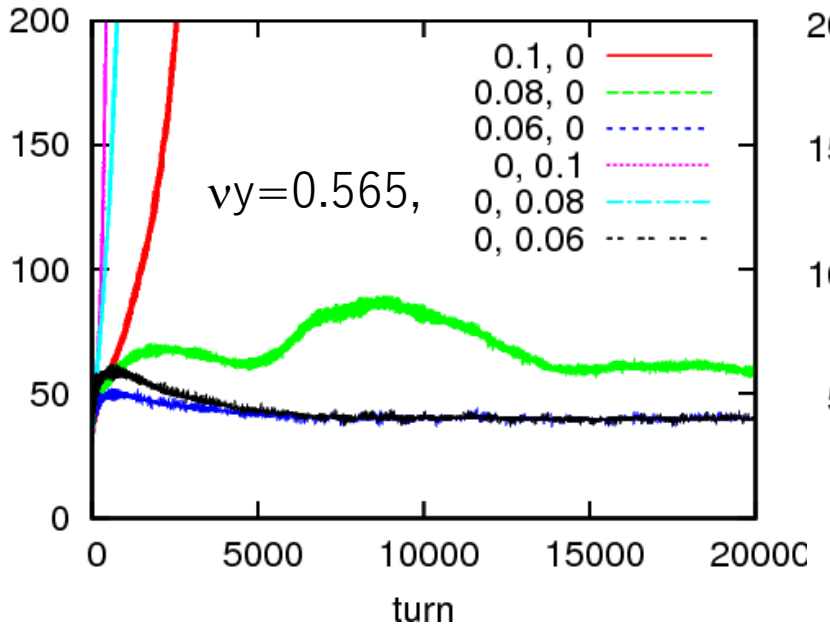
- E. Kikutani, Particle Accelerators 52, 251 (1996)
  - Z(t) dependent kick due to kicker wave form.

- Effects of BxB feedback on Head-tail mode is reported based on the above ideas.

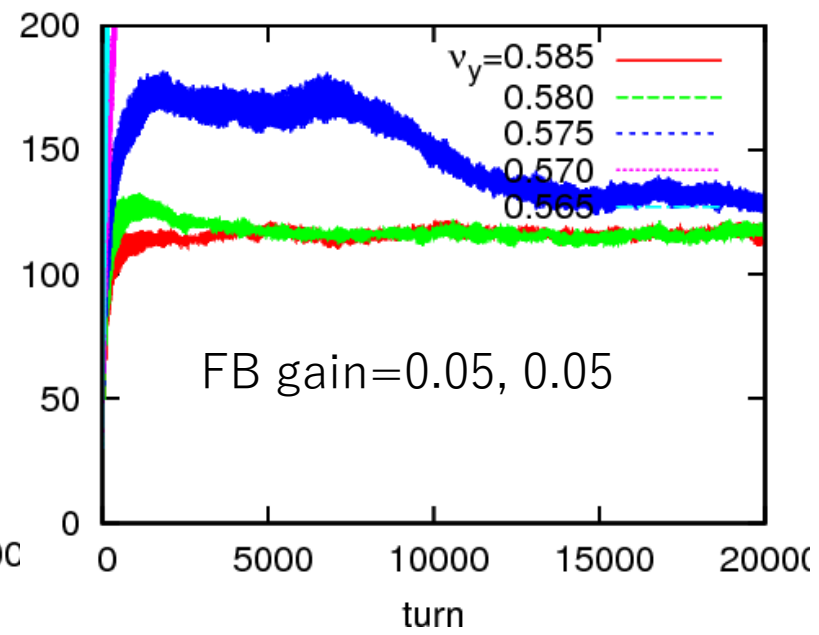
FB gain and collimator offset

FB Gain scan for yw=1mm



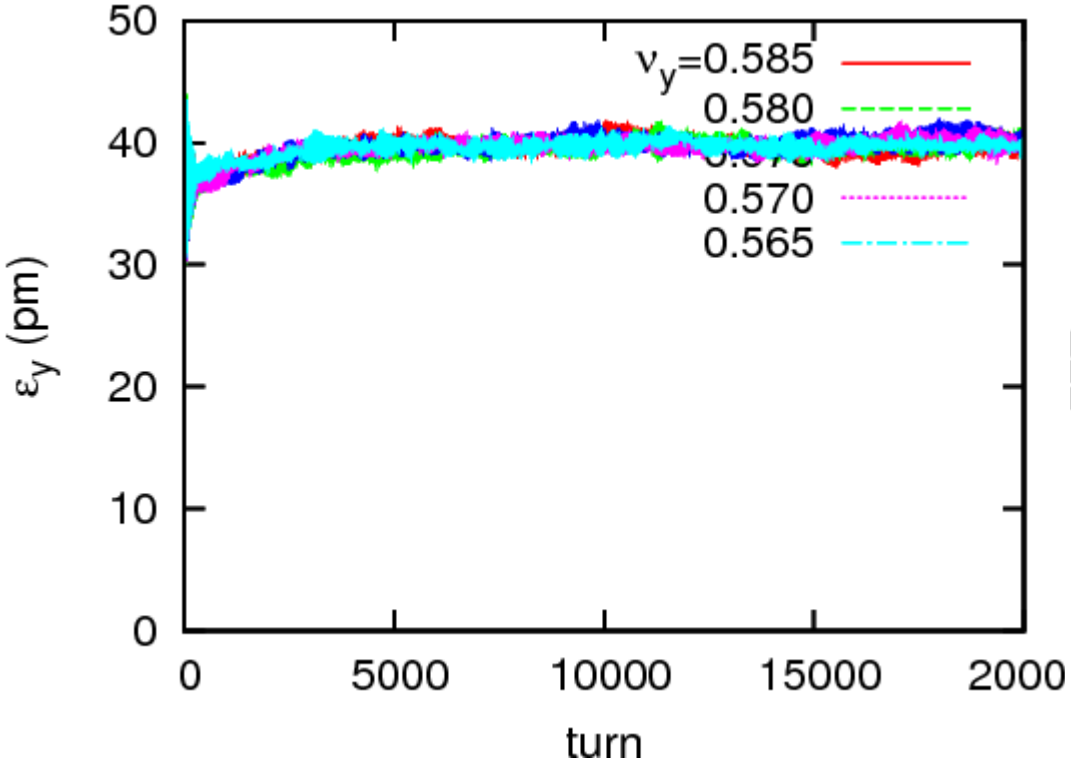


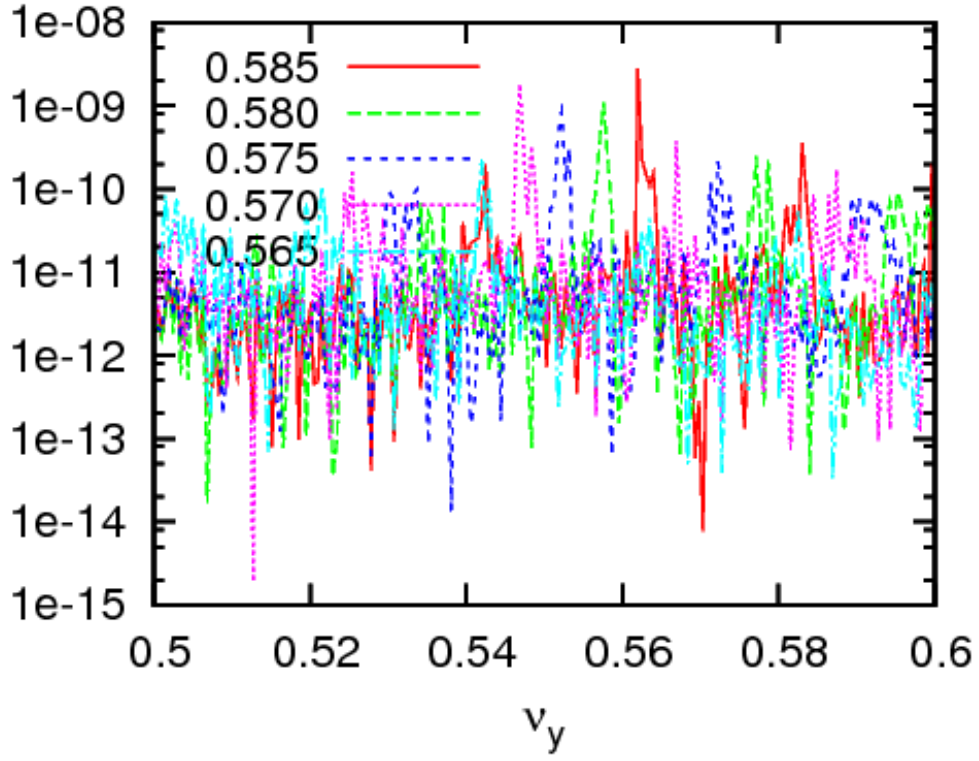
tune scan for yw=3mm



1 tap resistive feedback

- Simplest feedback model
- Use 2nd feedback loop, FB gain 0.1. No growth at G=0.15.
- Choose ϕ(K2)= ϕ(M1)+0.25-ν_y(0.585).
- -1 mode is seen, but no emittance increase.





Activities

- 7th meeting (https://kds.kek.jp/event/41962/)
  - Mode analysis with BxB Feedback, K. Ohmi
  - LER single bunch blow-up measurement at Apr. 5., K. Ohmi
  - Machine study reports and PyHEADTAIL simulations using new wake, T. Ishibashi

- 6th meeting (https://kds.kek.jp/event/41322/)
  - -1 mode and BxB FB, K. Ohmi
  - Machine study report and impedance model updates, T. Ishibashi

- 5th meeting (https://kds.kek.jp/event/40778/)
  - Study of Head-tail instability, K. Ohmi
  - Report of machine studies, T. Ishibashi
  - PyHEADTAIL simulations for a situation of a machine study on Oct. 26th, 2021., T. Ishibashi
  - PyHEADTAIL simulations: concentrated or distributed wakefield, M. Migliorati

Members (29):
Alexei Blednykh
Demin Zhou
Emanuela Carideo
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Hiroyuki Nakayama
Hitomi Ikeda
Katsunobu Oide
Kazuhito Ohmi
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Keisuke Yoshihara
Makoto Tobiyama
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Mika Masuzawa
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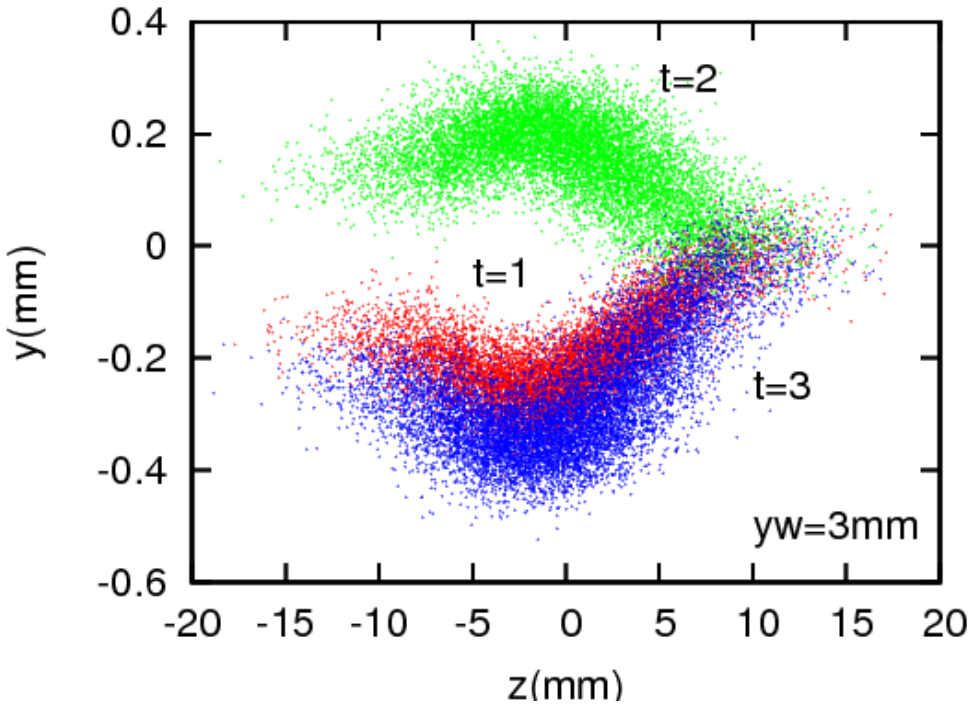
Nicolas Mounet
Takeshi Nakamura
Rogelio Tomas
Sven Vahsen
Shinji Terui
Tadashi Koseki
Masaru Takao
Takuya Ishibashi
Tom Browder
Tor Raubenheimer
Na Wang
Yong-Chul Chae
Yoshihiro Funakos
Yusuke Suetsugu

Activities

- 4th (https://kds.kek.jp/event/40154/)
  - ECHO3D and its application, I. Zagorodnov
  - Computation of the impedance of collimators in the LHC, N. Mounet
  - Impedance Model Updates, T. Ishibashi
  - Analysis of the Bunch Oscillation Recorder, K. Ohmi
  - Convergence studies and wakes for vertical collimators in ECHO3D, T. Ishibashi
  - Convergence study of PyHEADTAIL, T. Ishibashi
- 3rd (https://kds.kek.jp/event/39972/)
  - Impedance model for SuperKEKB LER, D. Zhou
  - Update on machine studies, T. Ishibashi
  - Beam dynamics simulations with the updated wake, M. Migliorati
  - Laslett tune shift in SuperKEKB and J-PARC MR, K. Ohmi
  - Synchro-beta resonance chromatic coupling and wake force, K. Ohmi
  - Convergence study of vertical collimators with GdfidL, T. Ishibashi
- 2nd (https://kds.kek.jp/event/39472/)
  - Machine study items and so on, T. Ishibashi
  - Impedance calculations of collimators with simple geometries, D. Zhou
- 1st (https://kds.kek.jp/event/39138/)
  - Welcome, introduction and presentation of the subgroup, M. Migliorati
  - Introduction of TMCI members, collimators, tune shift and instability measurements, T. Ishibashi
  - Impedance and wakefield model, D. Zhou
  - TMCI and localized impedance, K. Ohmi

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.