Impedance and instability studies at SuperKEKB

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eeFACT2022, Frascati, Italy

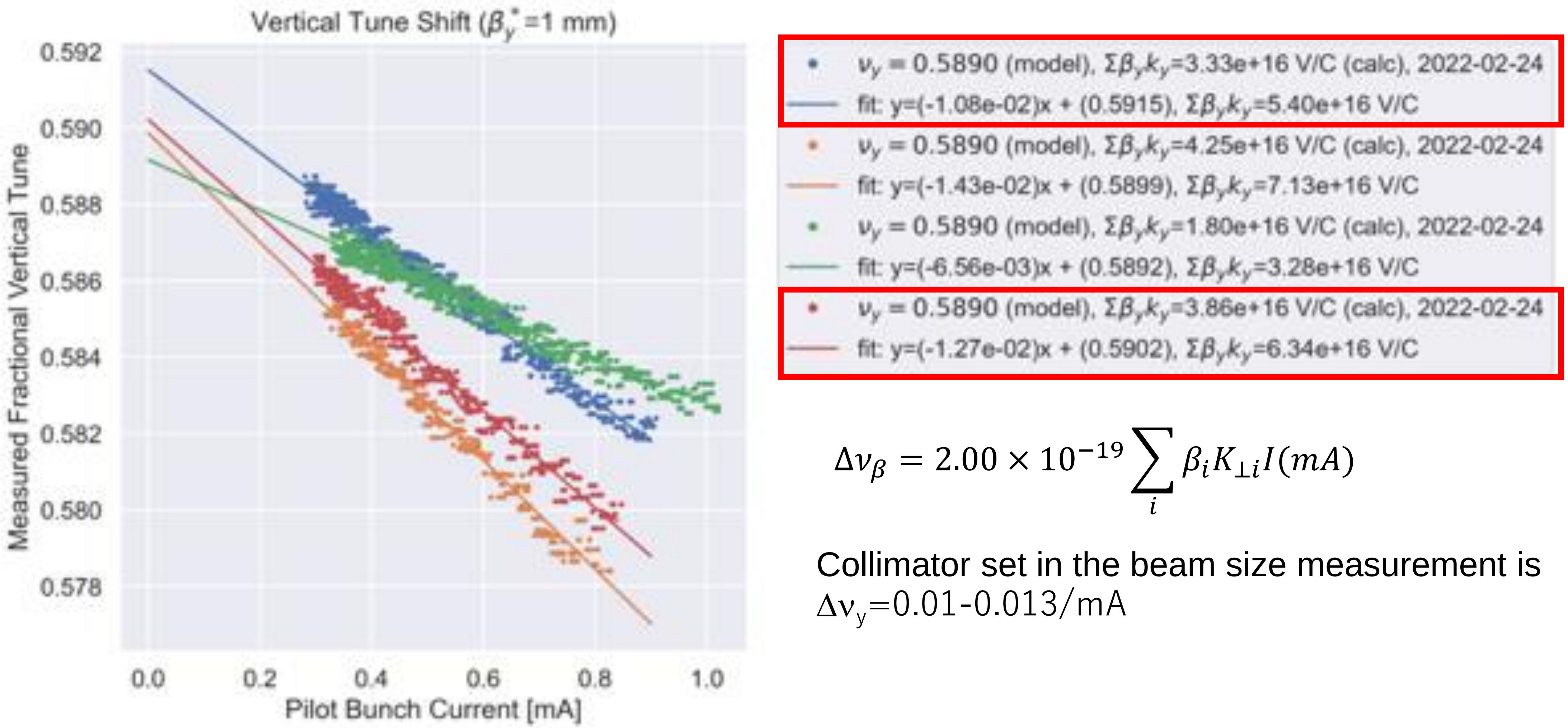
Sep. 12-15, 2022

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 ν_y<0.6 and is serious at ν_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 (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 suppressed at BxB feedback OFF.

Tune shift

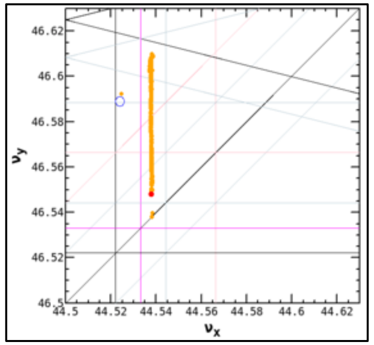


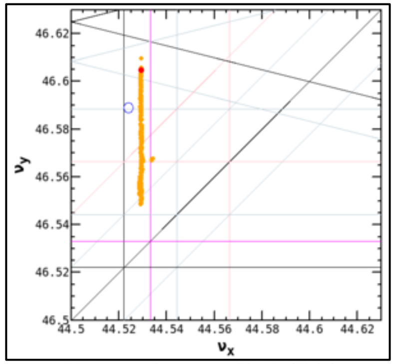
$$\Delta\nu_\beta = 2.00 \times 10^{-19} \sum_i \beta_i K_{\perp i} I(mA)$$

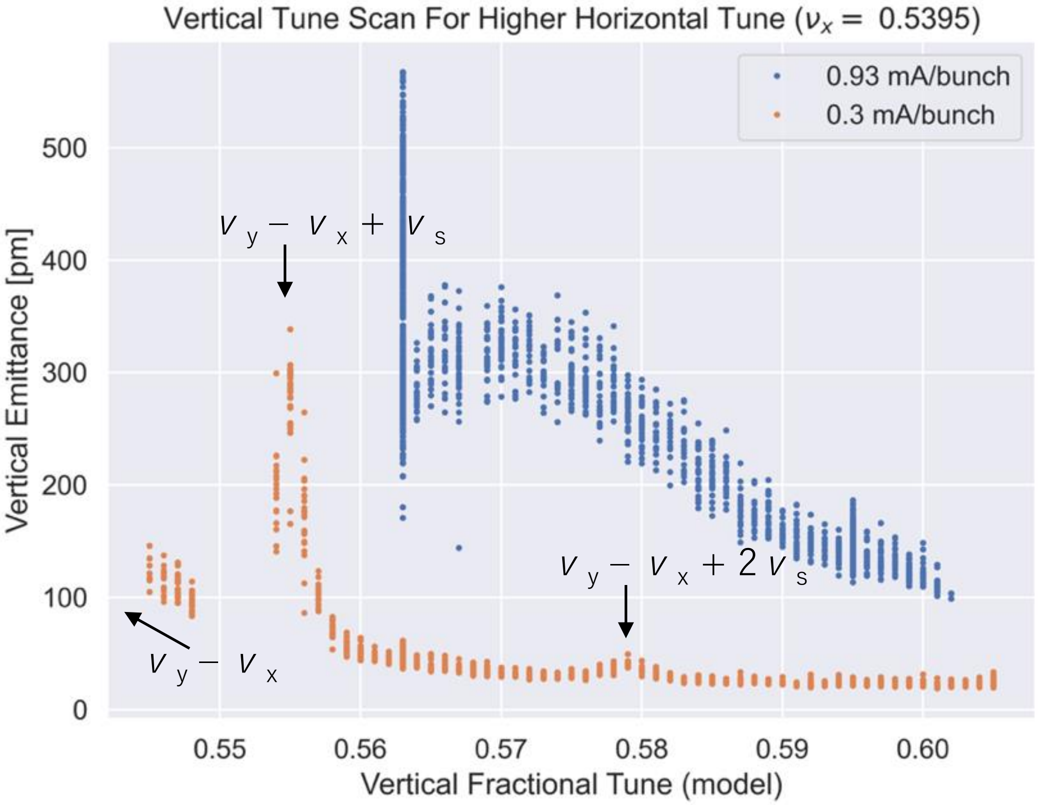
Collimator set in the beam size measurement is $\Delta\nu_y$=0.01-0.013/mA

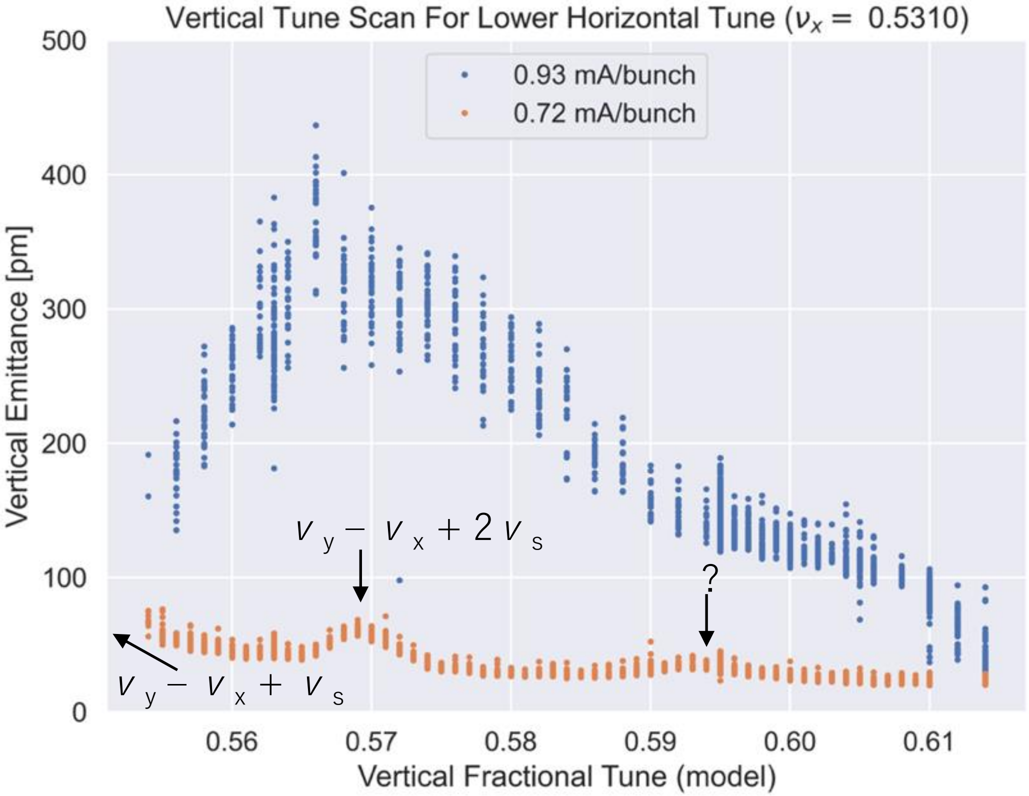
Tune Survey

No collision
Set kβ=36.1x10^15 V/C



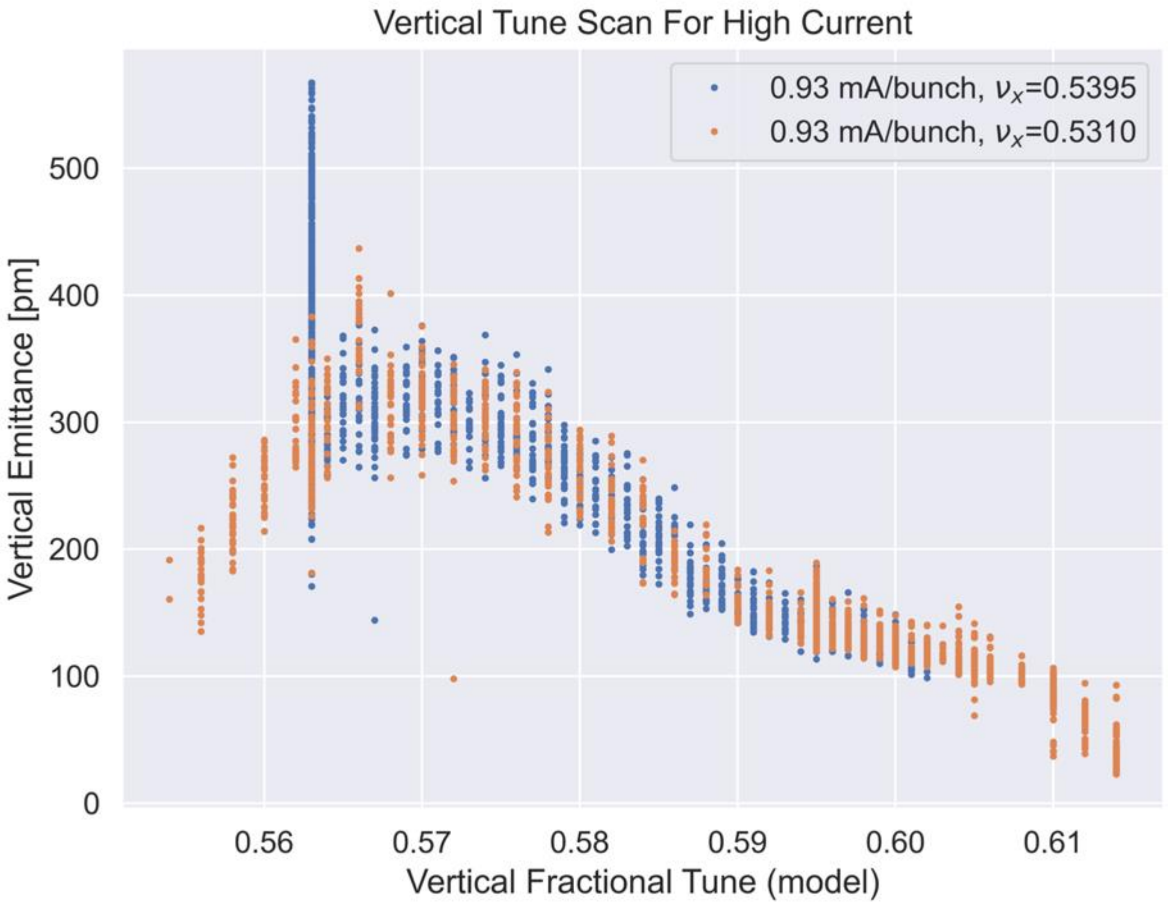






- The stop-band is remarkably spread when the instability occurs.
- The vertical emittance is getting smaller for higher vertical tunes.
- We can see a small stop-band around 0.595 with the middle bunch current of 0.72 mA/bunch (ν_x = 0.5310).
- It had been difficult to inject in ν_y = 0.6 or above,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

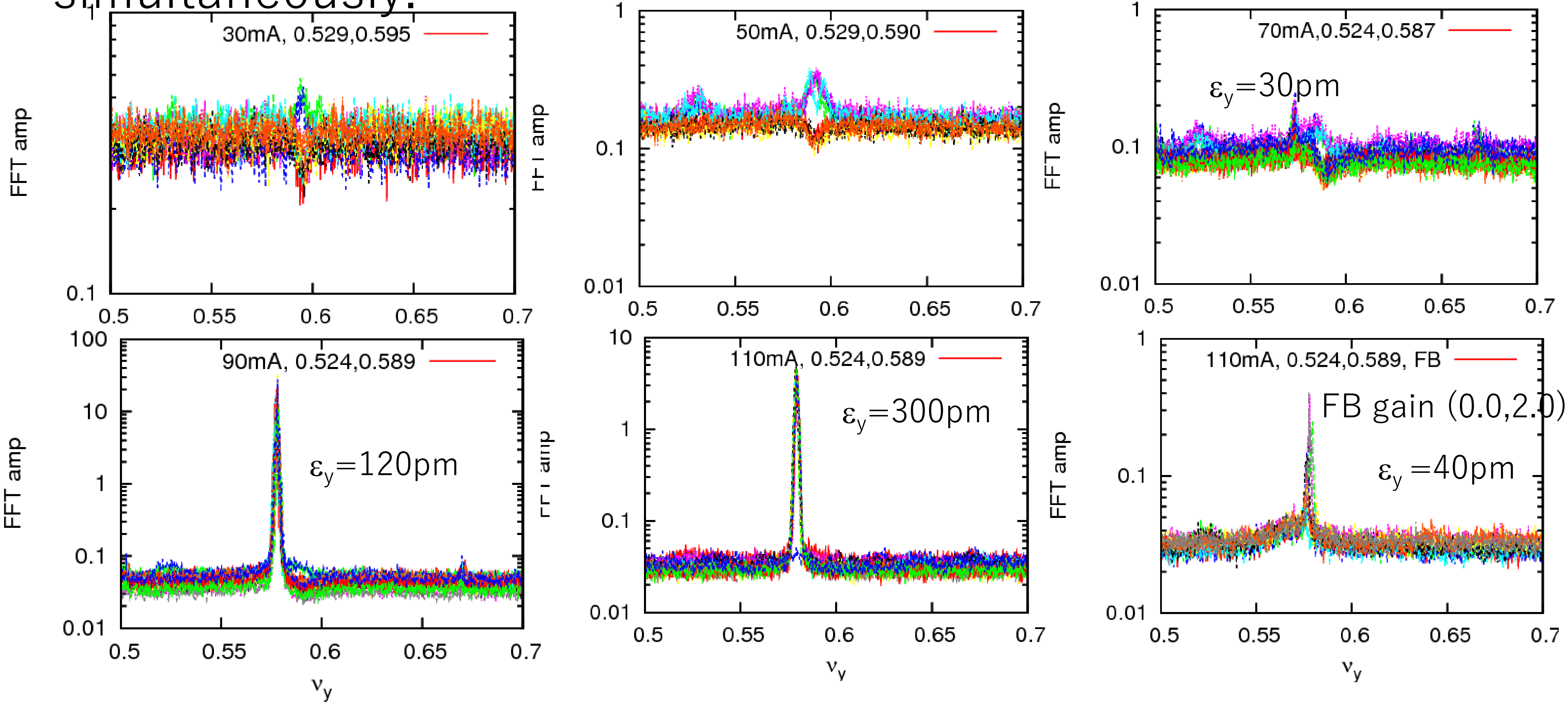
Tune Survey



- 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.

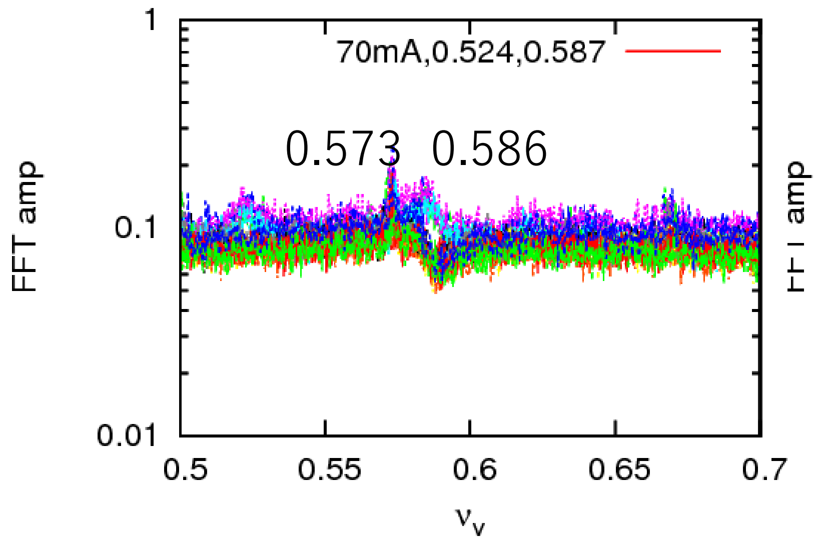
Bunch Oscillation Recorder spectra

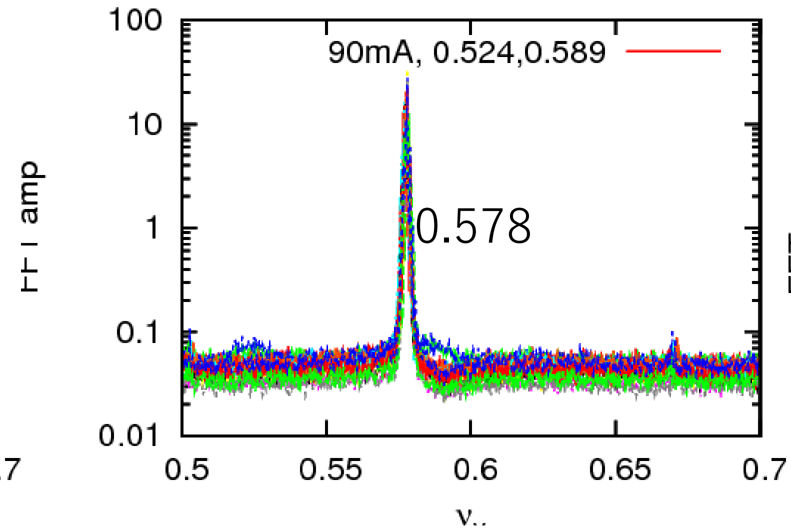
- Tune 0.524,0.590, 100bunch, I=0.3-1.1mA/b.
- Emittance growth and tune peak ~0.57 appear simultaneously.

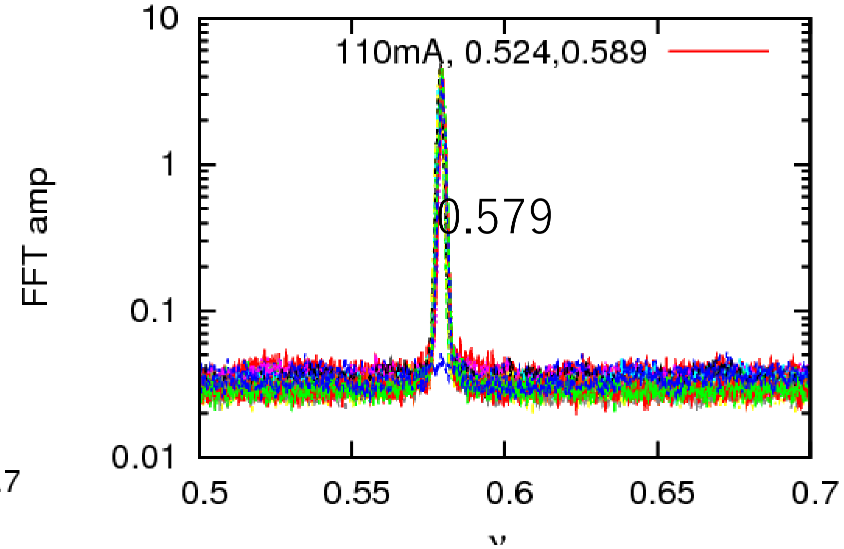


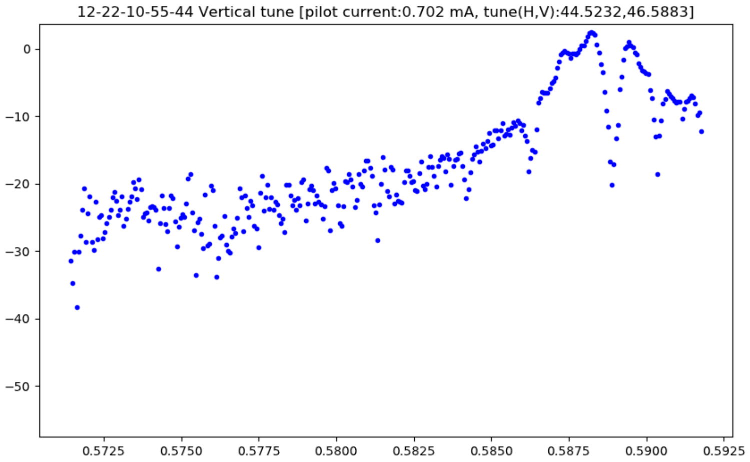
BOR and Pilot bunch spectra

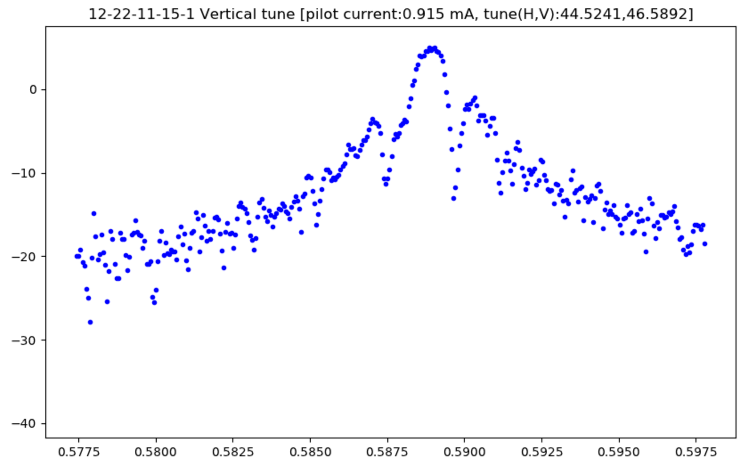
Pilot bunch: Tail bunch, BxB feedback inactive

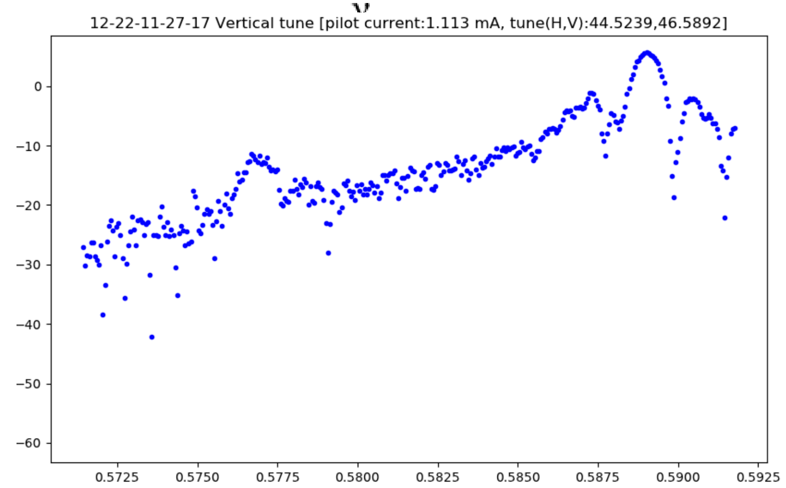










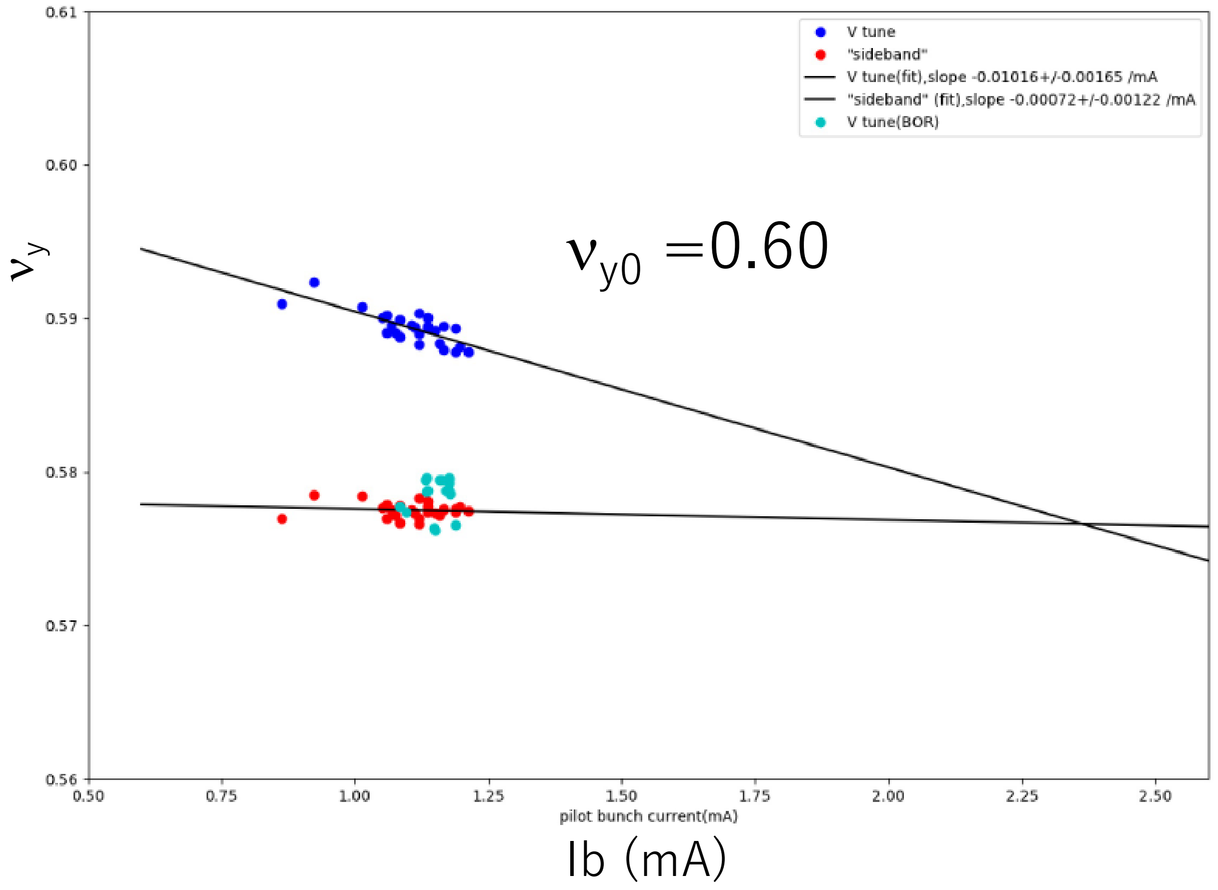


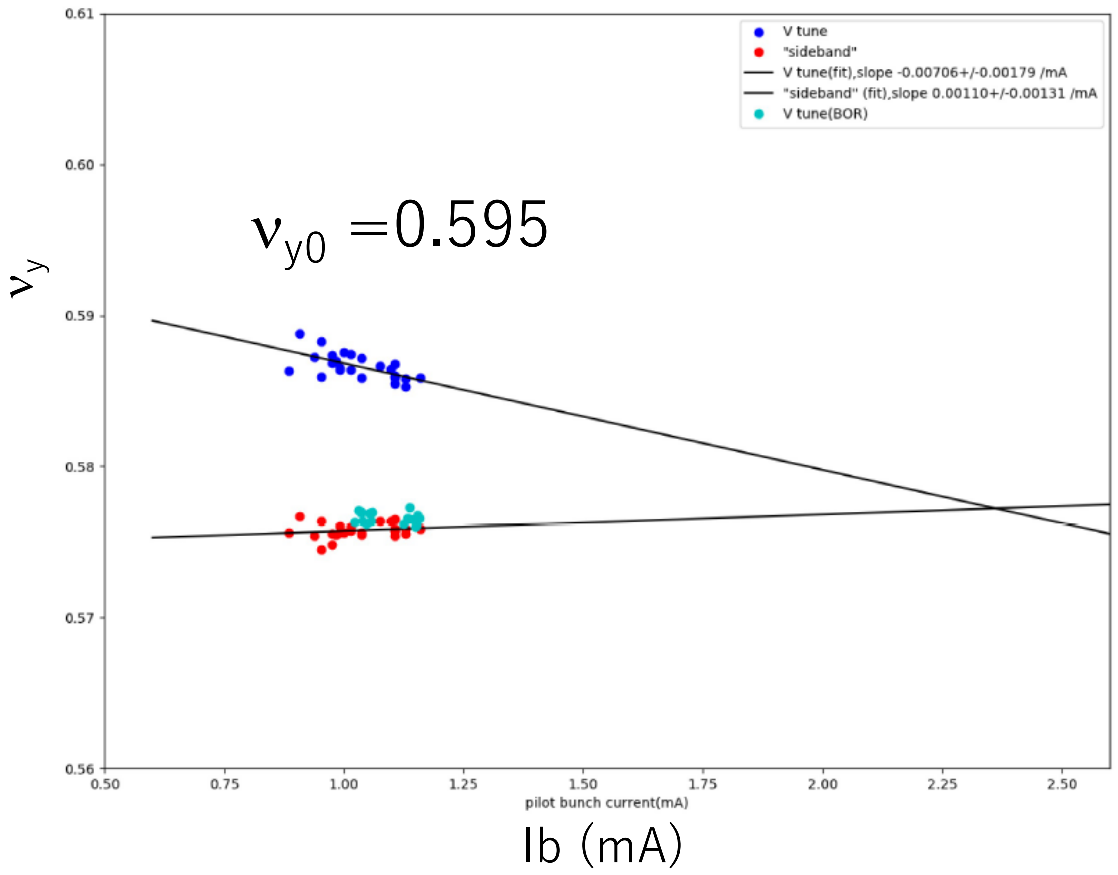
Courtesy H. Fukuma

Gated tune and BOR

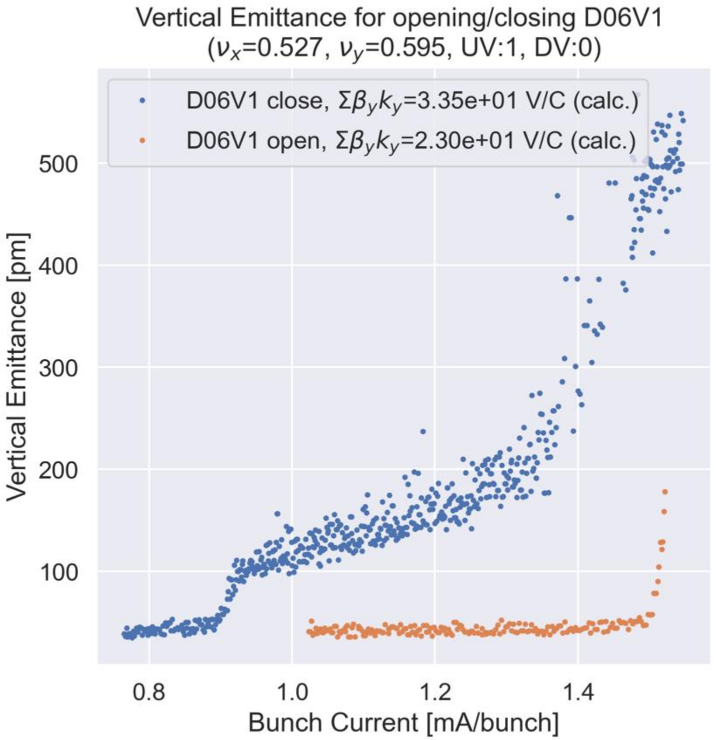
- Gated tune of the pilot bunch, tune ν_y and sideband ν_y-ν_s.
- BOR data of whole bunches
- Peak seen in BOR is -1 mode ν_y-ν_s

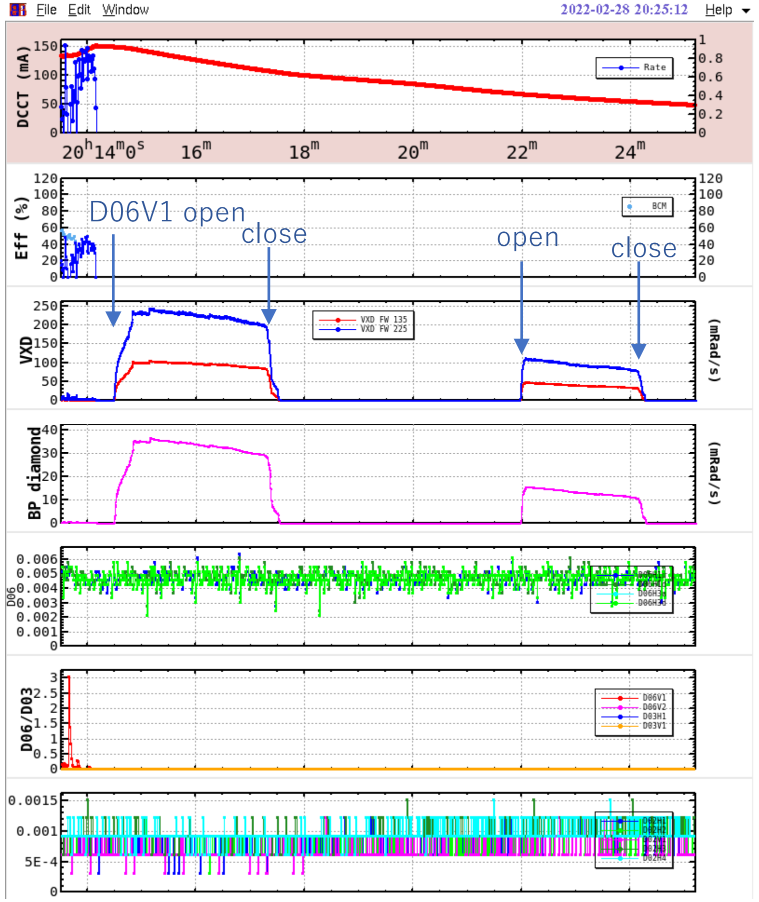
Courtesy H. Fukuma

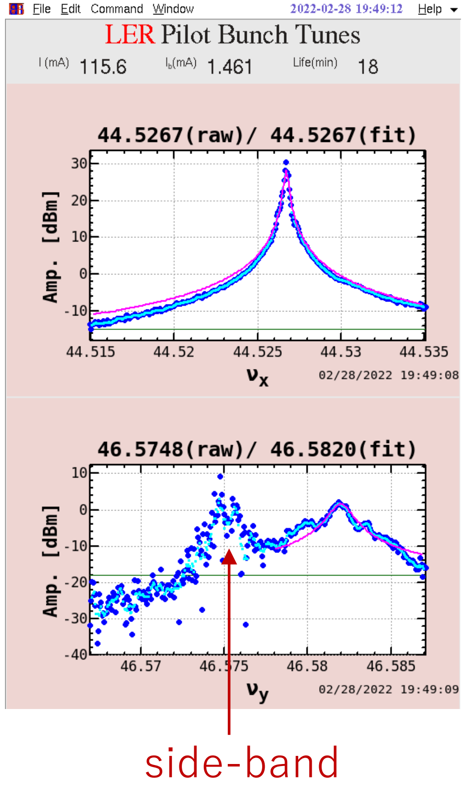


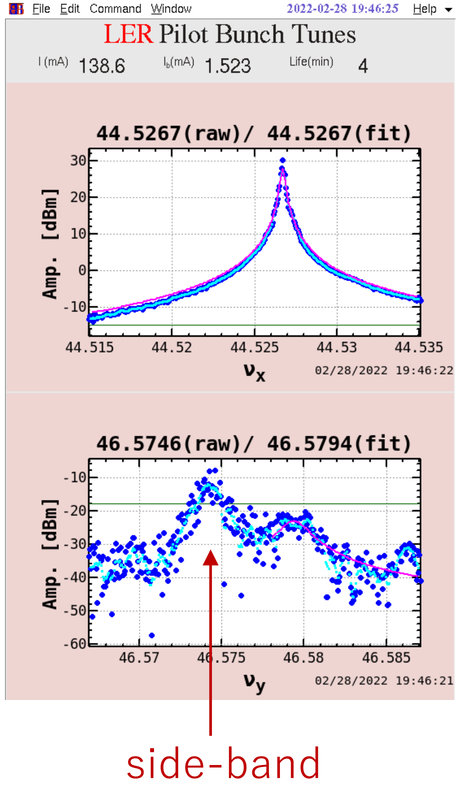


Vertical Emittance w/wo D06V1





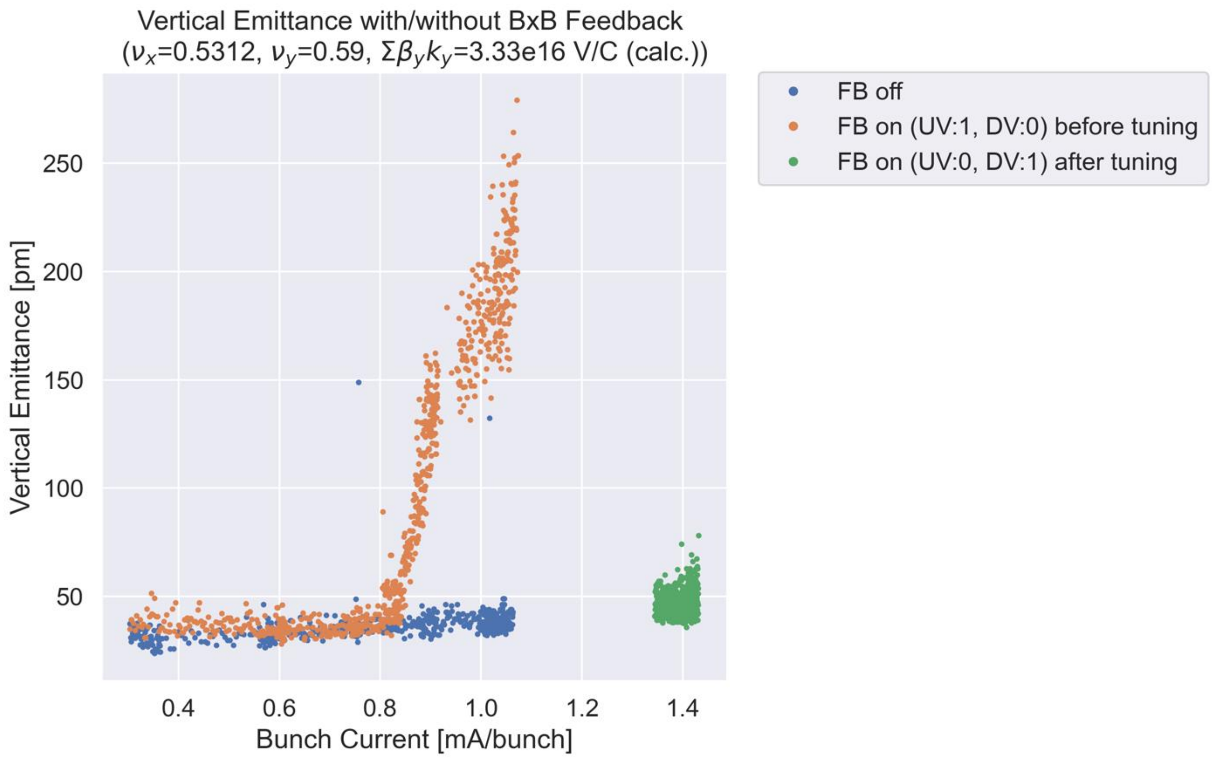


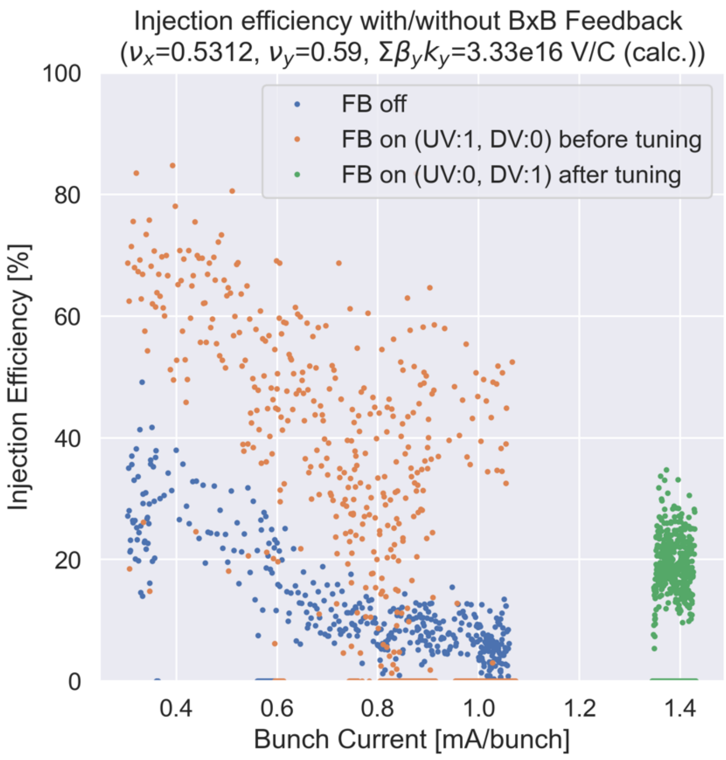


- When we fully opened the aperture of D06V1, the vertical emittance blow-up didn't occur up to ~1.5 mA/bunch.
  - (D06V1 aperture) close: ±2.9 mm, open: ±8 mm
- The background level derived from the storage beam increased when we opened it. We've used D06V1 as a primary collimator to cut off the injection 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

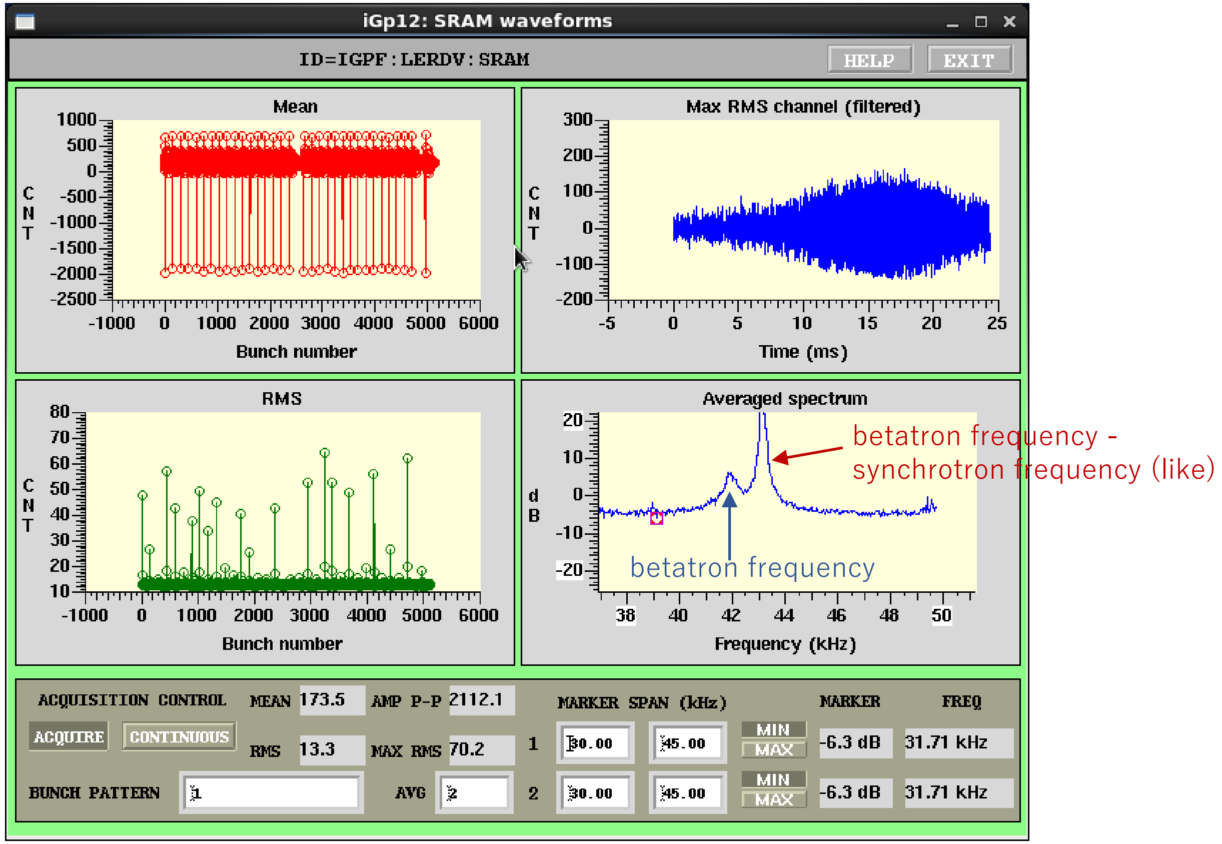




- We observed the vertical emittance with turning on/off the feedback (FB) with small number of the bunches to avoid multi-bunch instabilities.
- When we turned on the FB, the blow-up occurred around 0.85 mA/bunch.
- When we turned off the bunch-by-bunch FB, the vertical emittance blow-up didn't occur 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

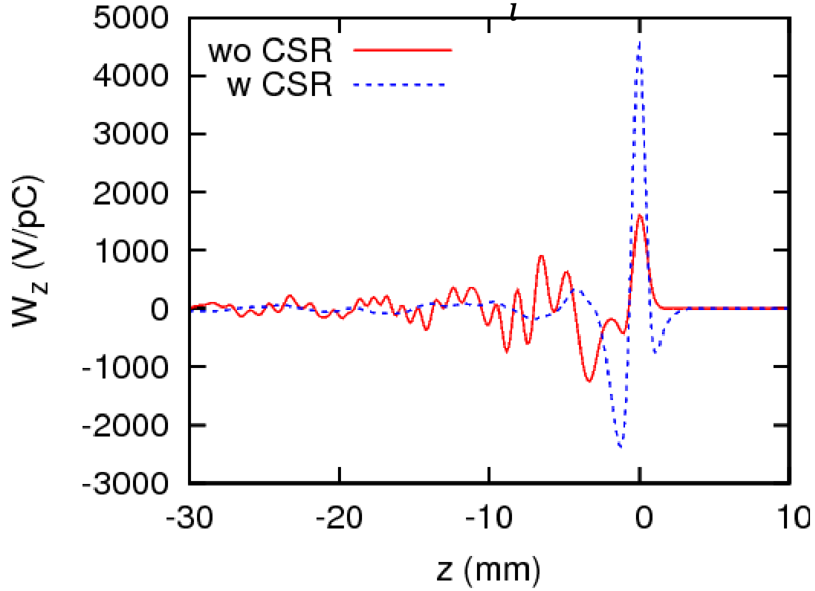
- Beam size increases when -1 mode appears at ~0.9mA.
- The 0 and -1 modes are not coupled at the current. The threshold of TMCI is ~2mA.

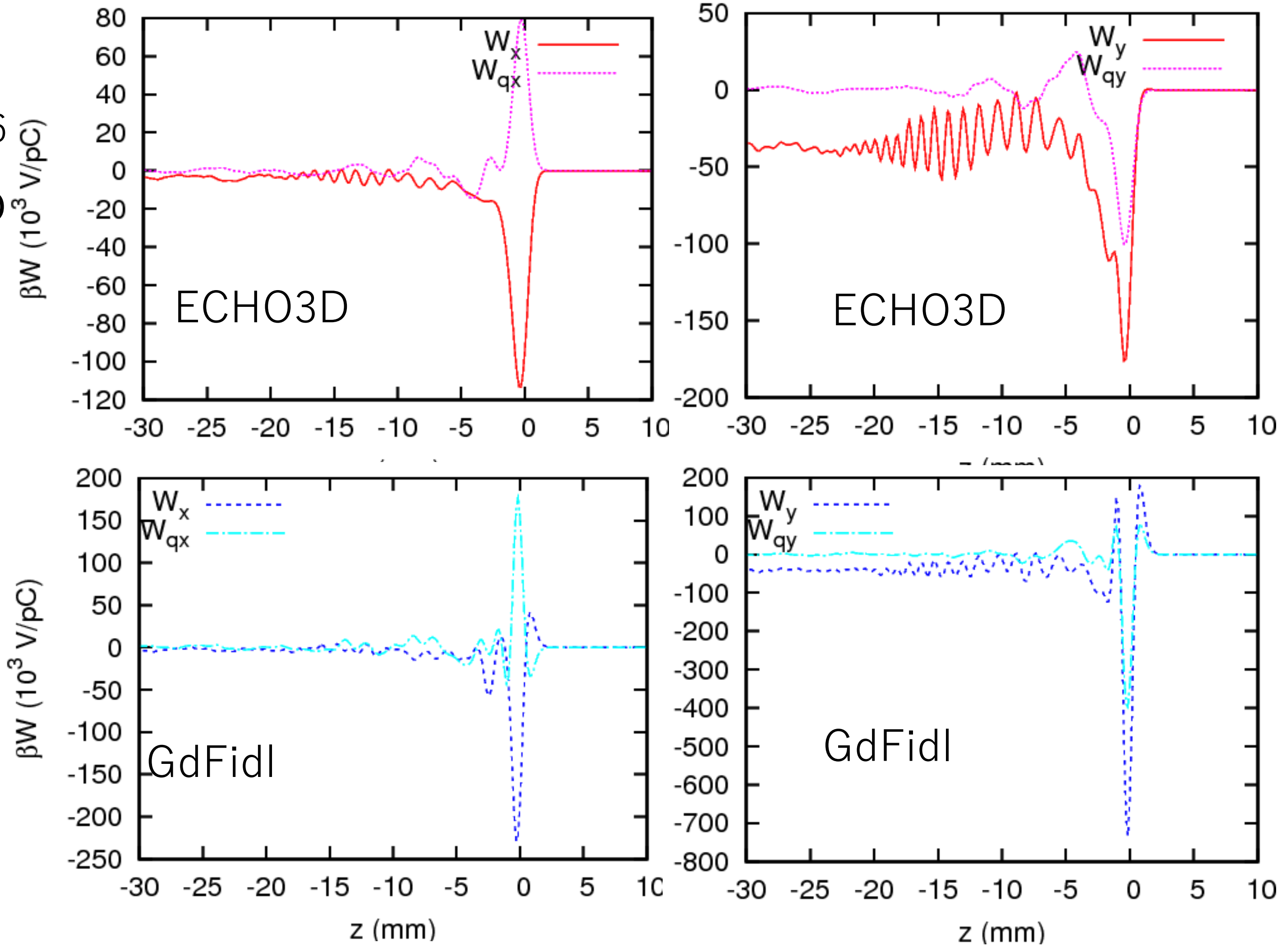
- Studies considering both the impedance and bunch-by-bunch feedback are necessary.

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

- Kick Factor $\beta_y K_y$, $\beta_y K_{qy}$ (V/C)
  - GdFidl -3.84×10^{16}, -1.27×10^{16} $\Delta\nu_y=0.01$/mA
  - ECHO3D -3.18×10^{16}, -0.84×10^{16} $\Delta\nu_y=0.008$/mA. Multiply 1.25 to get measured tune shift $\Delta\nu_y=0.01$/mA

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

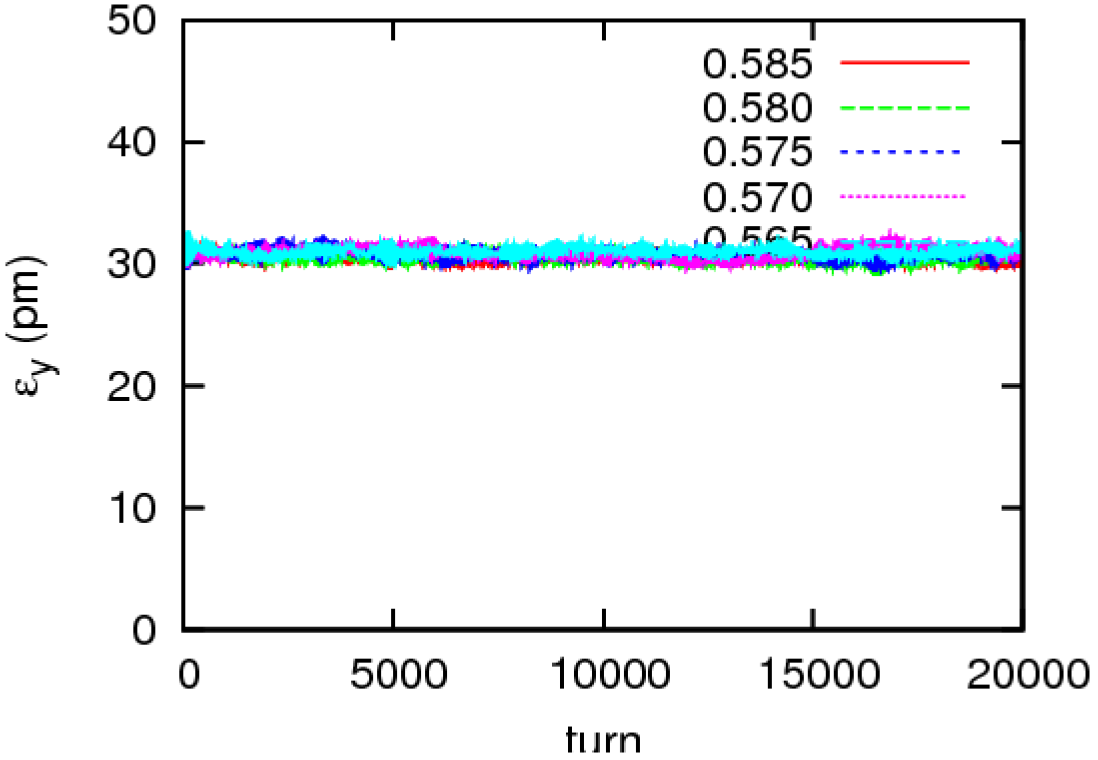


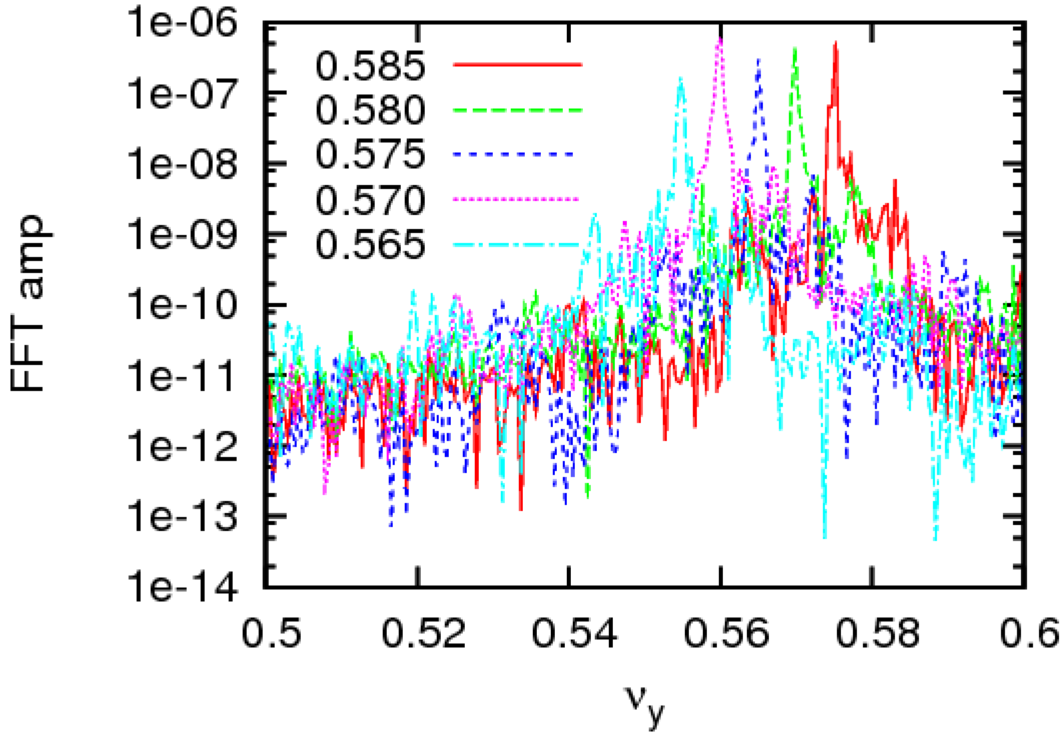


Simulation without feedback

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

0 mode is seen. Tune shift is 0.01/mA





- No emittance increase.

Bunch by Bunch feedback system in SuperKEKB-LER

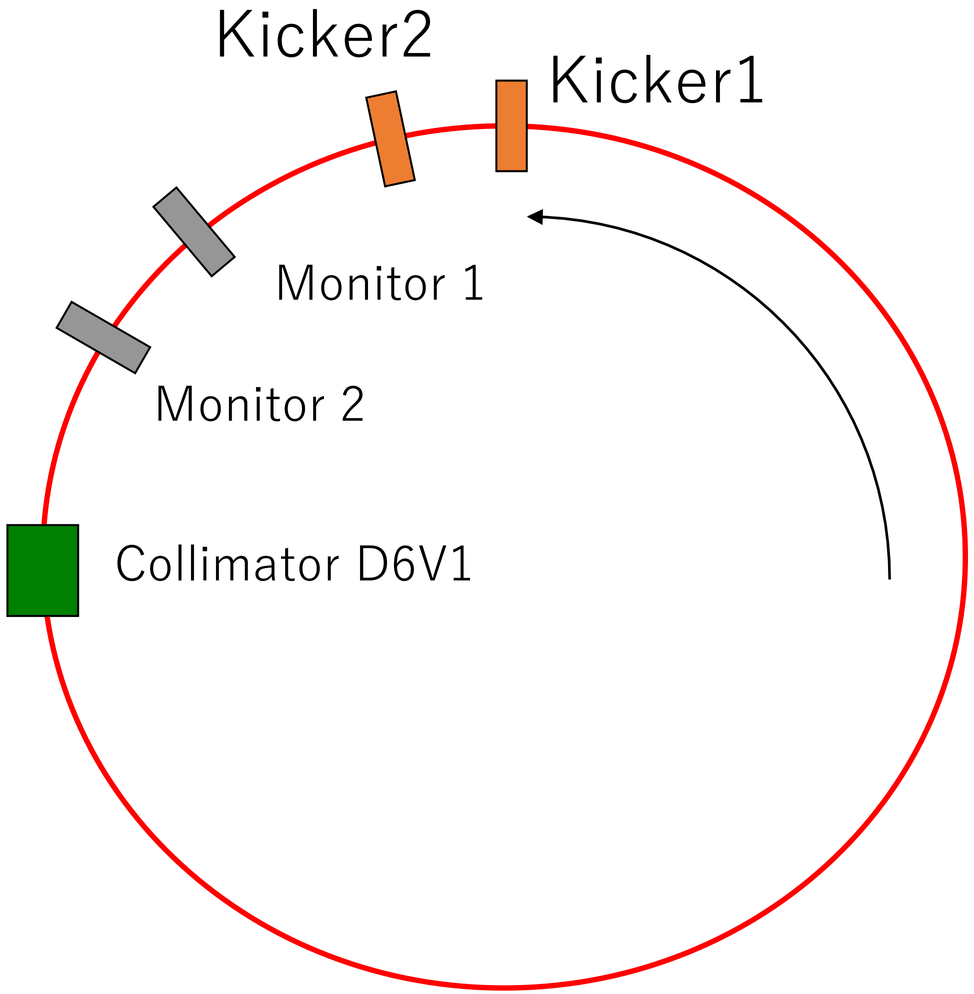
- 2 feed back loop working independently, TFBK1-FBMON1 and TFBK2-FBMON2
- Max 10 tap

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 $\mu=2\pi\nu$.

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

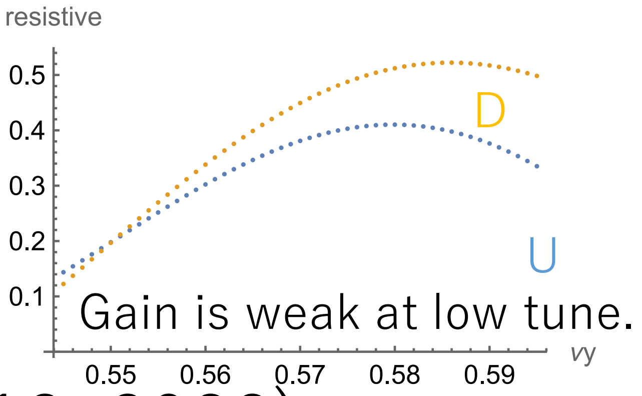
- Resistive and reactive components for FIR filter

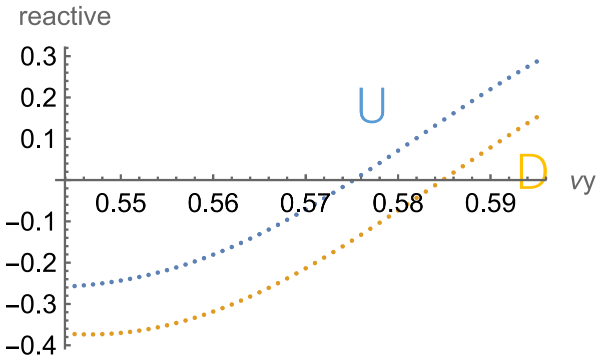
$$d_P = \frac{1}{2}\sum_{k=0}^{(N_{tap}-1)} c_{oef}(k)\sin(k\mu+\Delta\phi) \qquad d_X = -\frac{1}{2}\sum_{k=0}^{(N_{tap}-1)} c_{oef}(k)\cos(k\mu+\Delta\phi)$$

- 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.

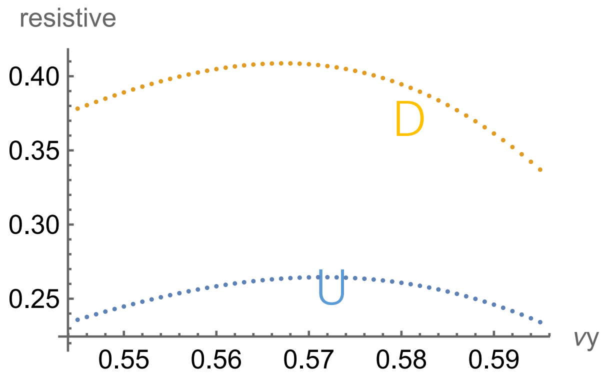
Resistive and reactive components

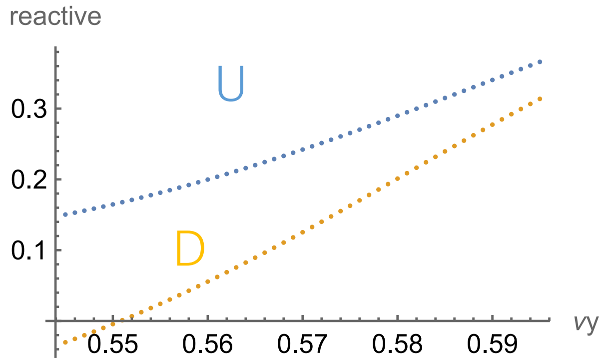
- Filter coefficients (~Mar. 11, 2022)
  - coef1={21623,-5530,-11430, 25925,-32767, 31362,-20832, 5288, 12317,-25956};
  - coef2={26781,-26182, 7149, 2479,-22777, 25564,-32767, 19752};





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





Simulation BxB feedback ON

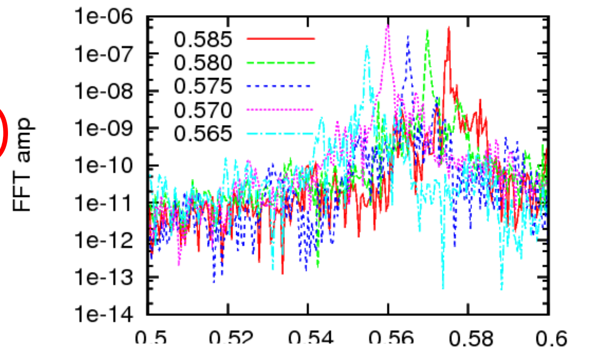
- The simulation considers the betatron phase phases of monitors, kickers and D6V1 collimator.

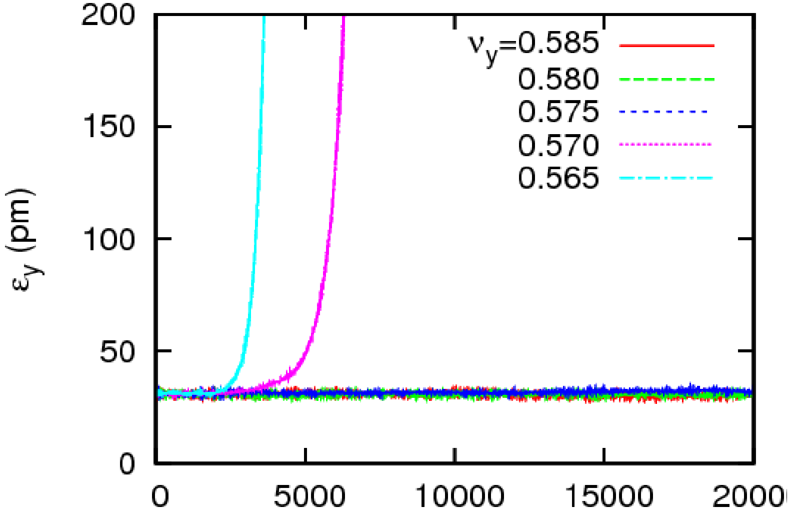
Vertical emittance and FFT y at 1mA/b

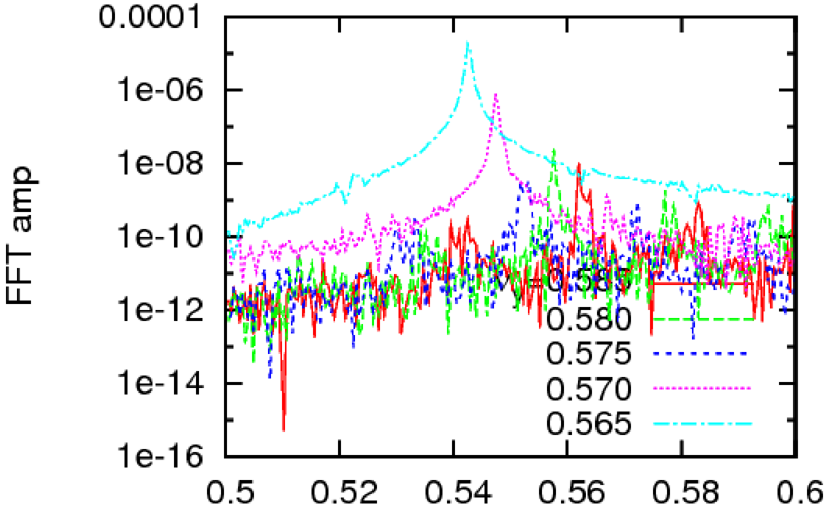
- First FBcoef (Mar. 11)

U D

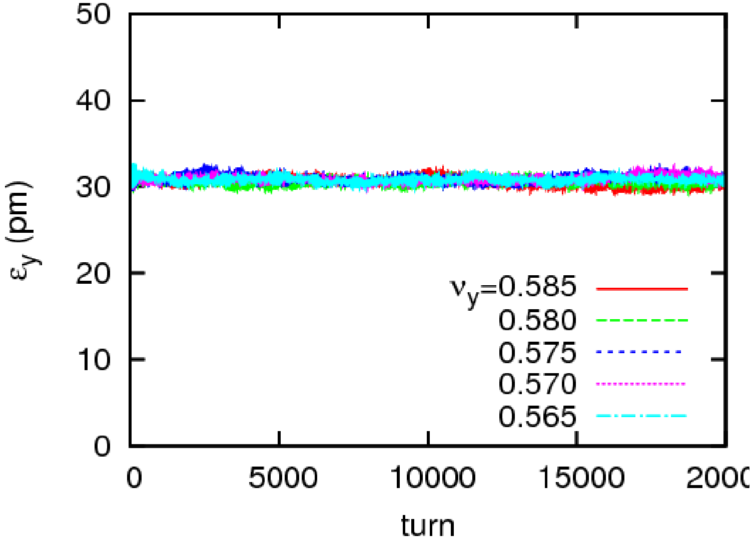
- G_{FB}=0.05+0.05

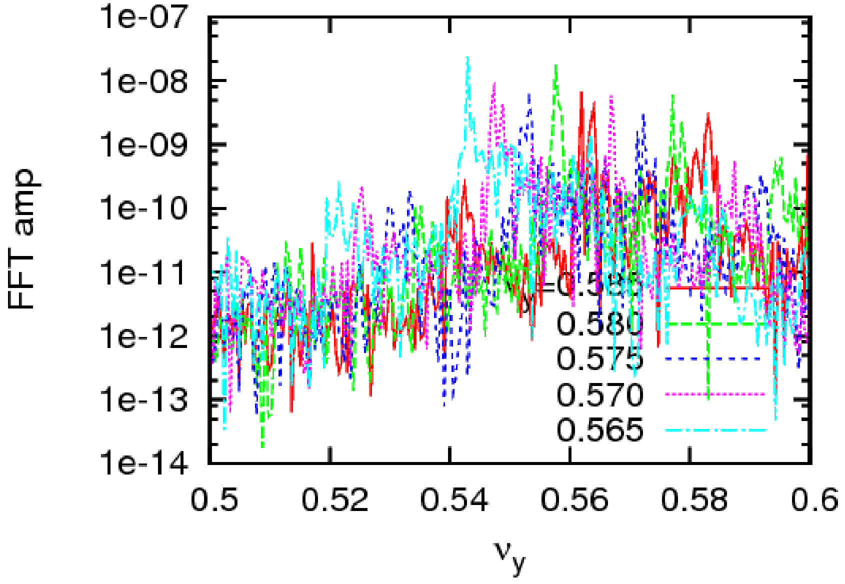






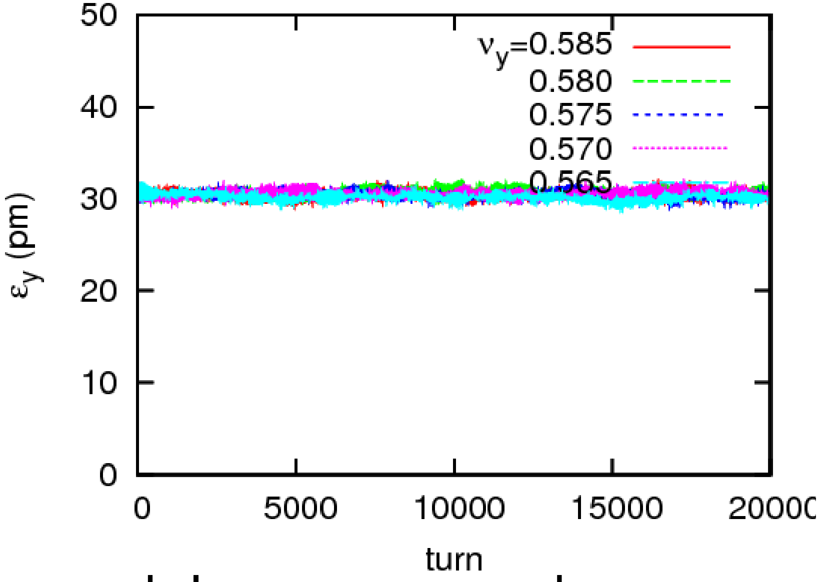
- G_{FB}=0.02+0.02

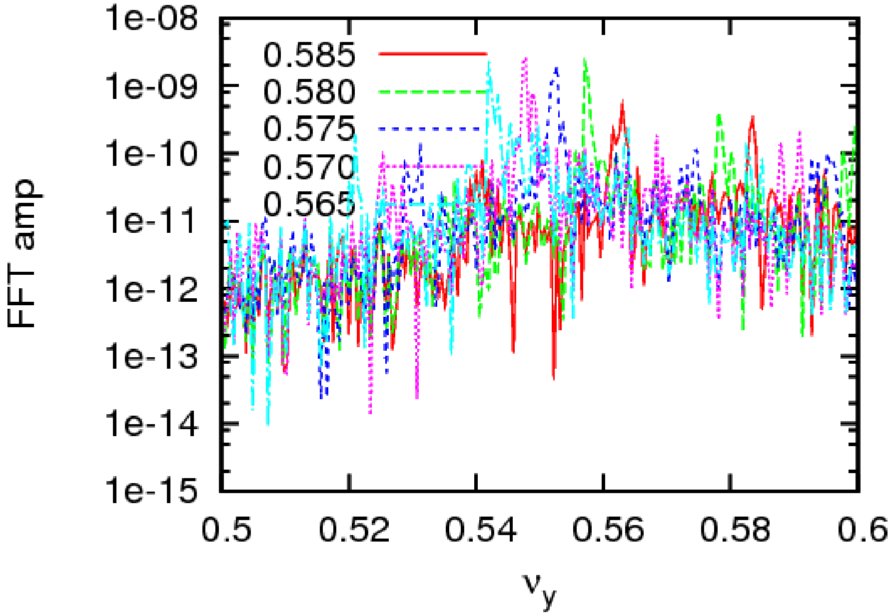




Vertical emittance and FFTy at I=0.5mA

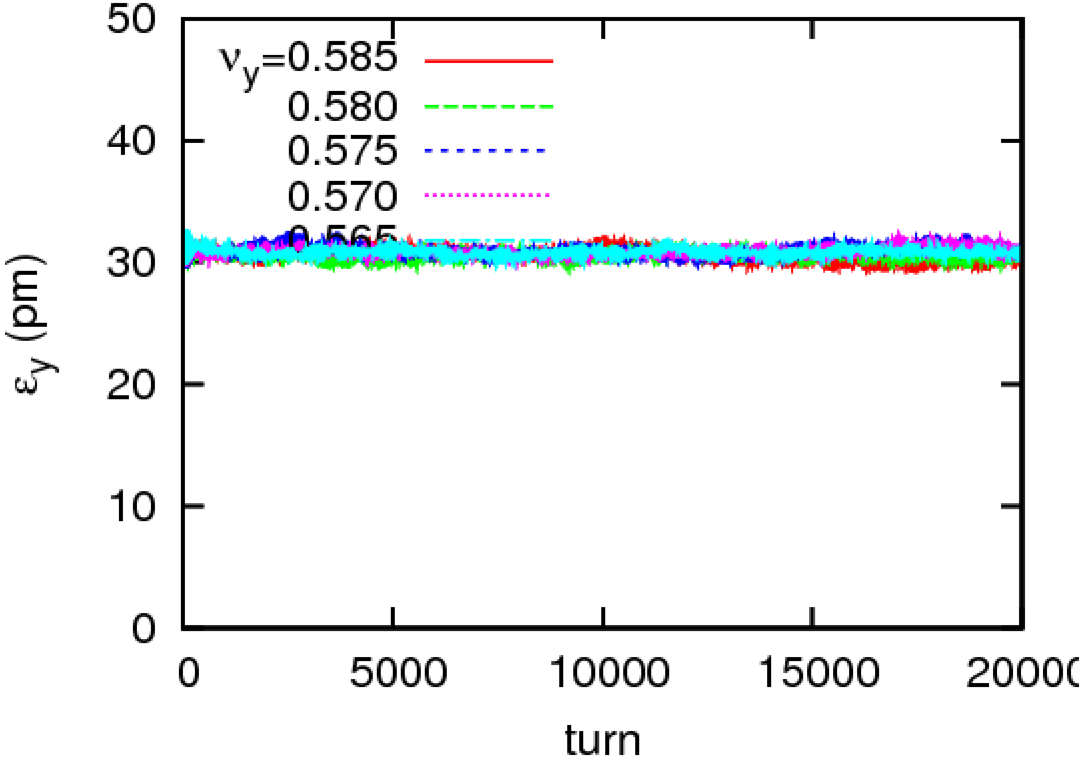
- First FBcoef (Mar. 11)
- G_{FB}=0.05+0.05
- No emittance increase at low current

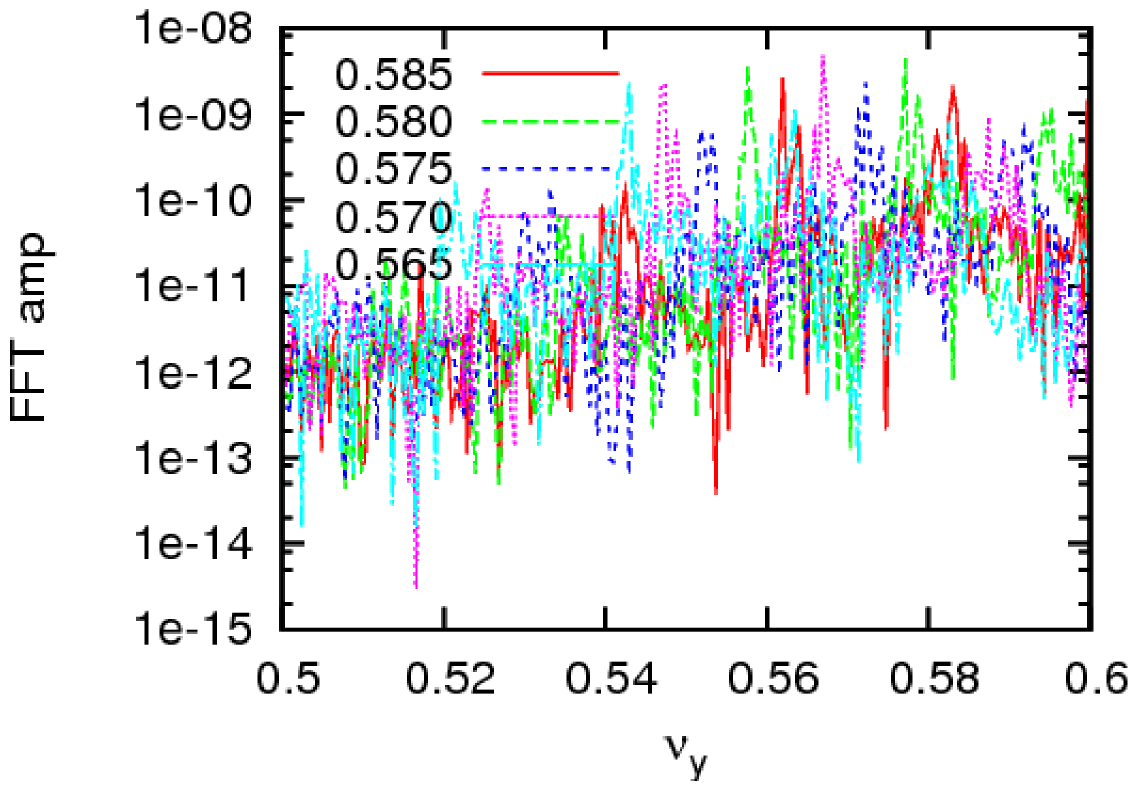




Vertical emittance and FFT of <y>

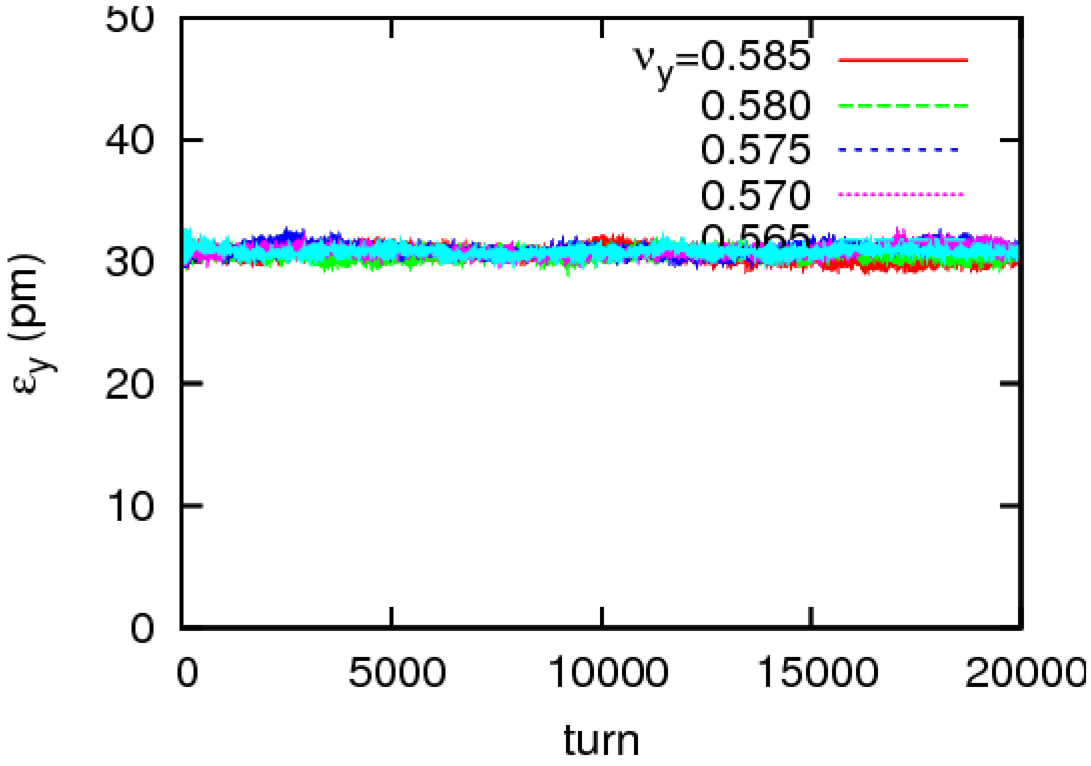
- Second FBcoef (Mar. 12)
- I=1mA/b
- Emittance increase at low ν_y is suppressed.

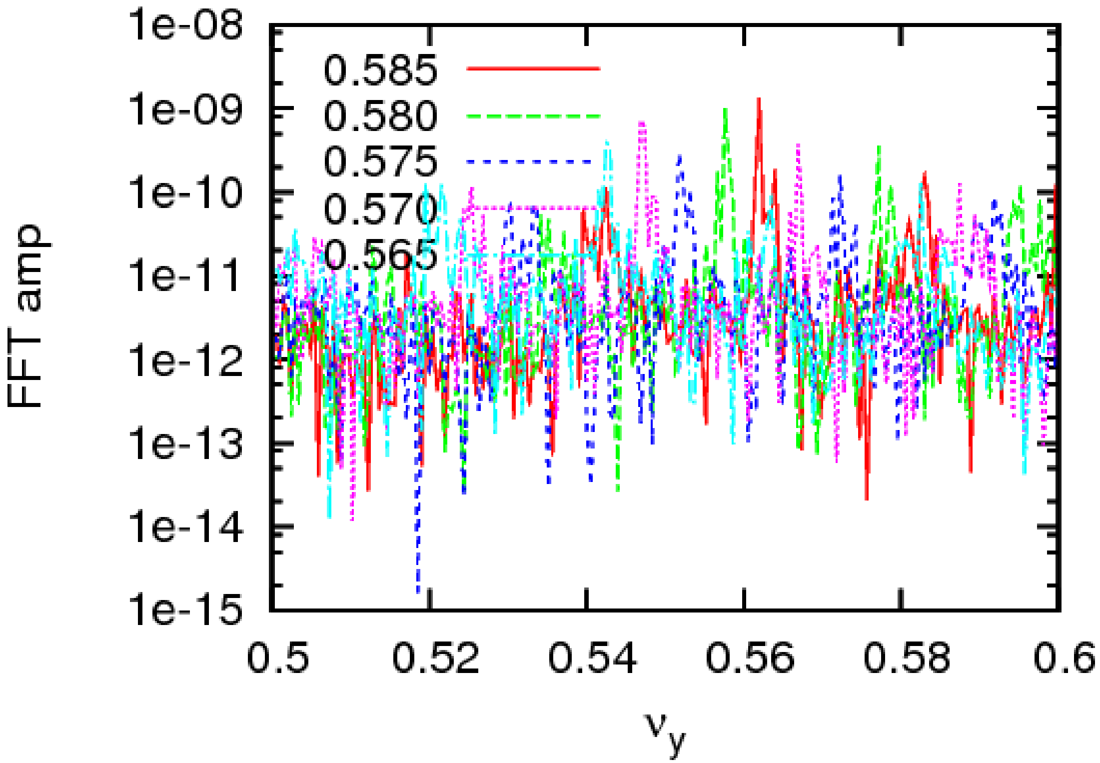




1 tap resistive feedback

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





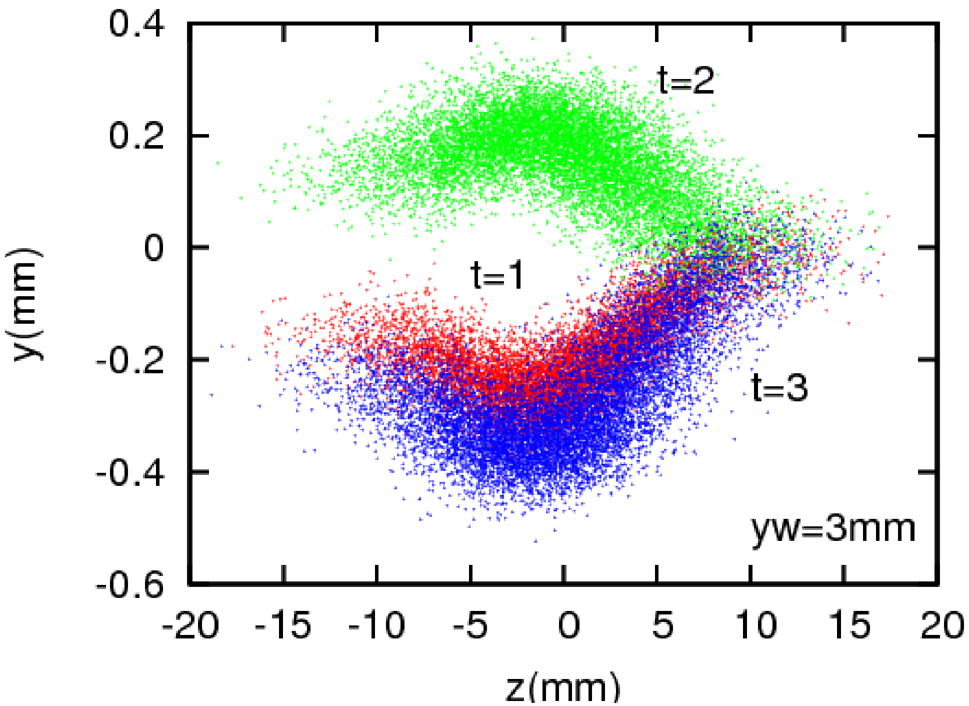
Summary for feedback

- Multitap (1st coef) and high gain feedback system (G=0.1) cause -1 mode instability.
- Multitap FB with 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 will be studied.

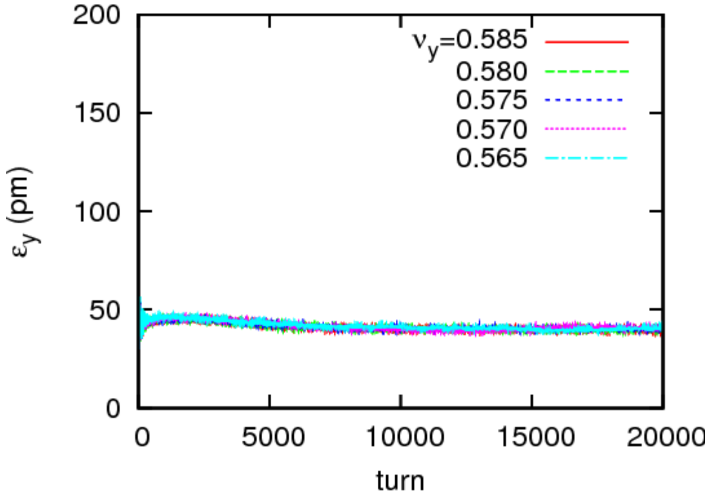
Effects of collimator offset

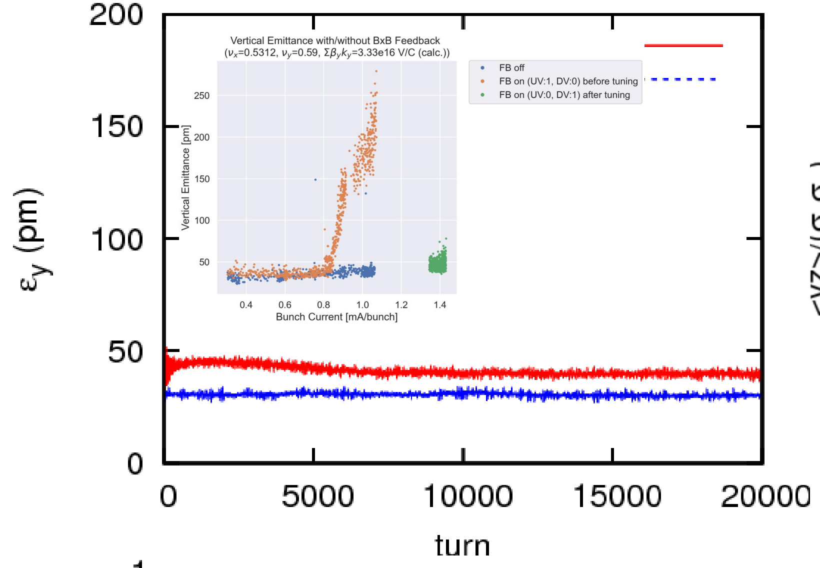
- Dipole kick depends on the longitudinal distribution
- Turn-by-turn change of y-z distribution for collimator offset 3mm at D6V1 is shown.
- An equilibrium distribution with a banana shape is formed after several radiation damping time.

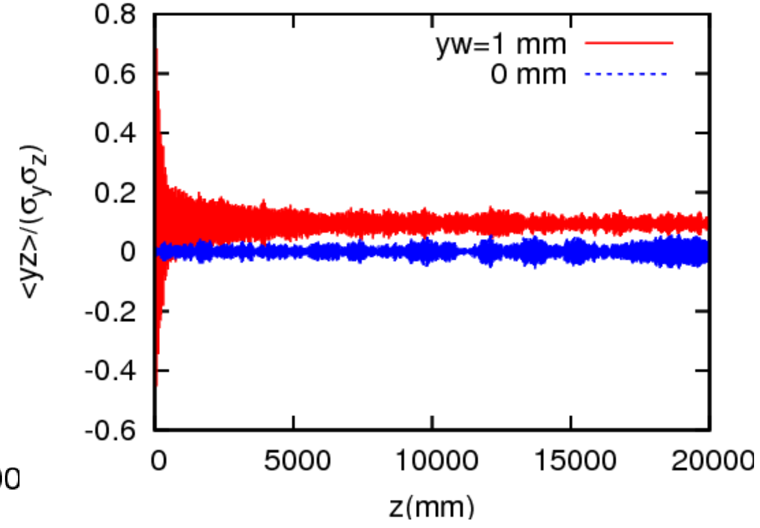


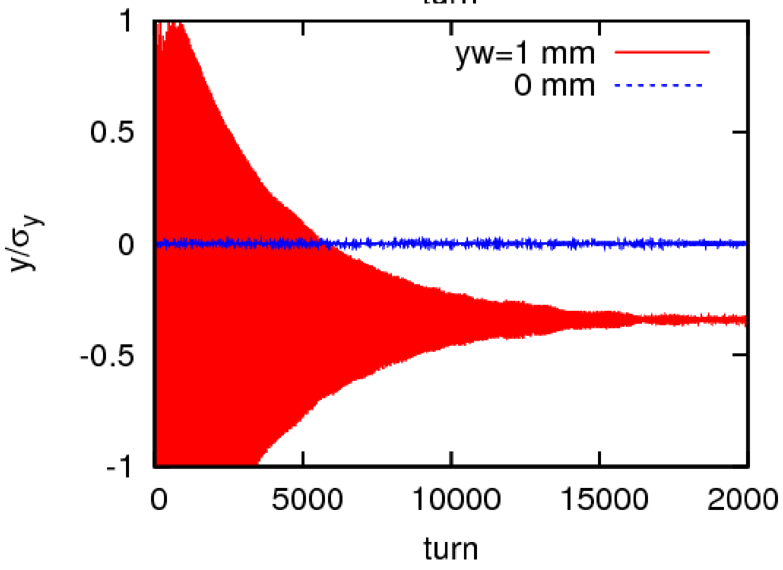
BxB FeedBack OFF with collimator offset 1mm

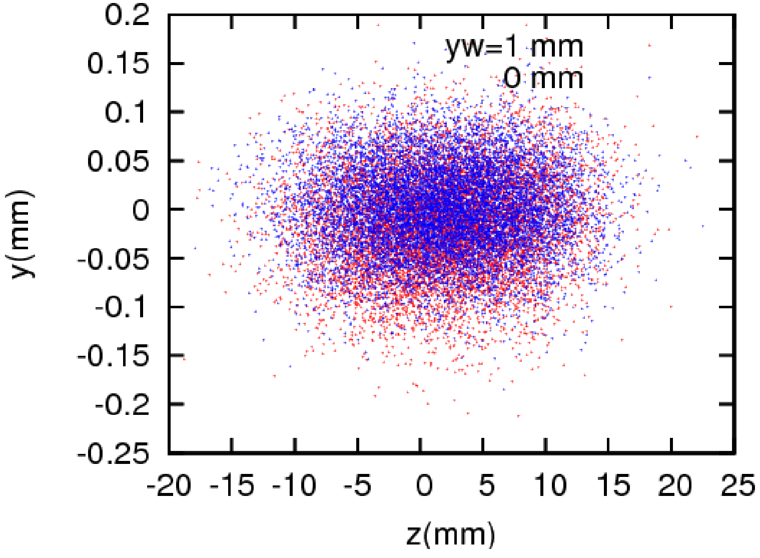
- Emittance increases 30->40pm at 1mA/b for collimator offset 1mm at D6V1.
- This may explain small emittance increase for the bunch current.
- Equilibrium orbit distortion as function of z. $\langle y\rangle=0.3\sigma_y$, $\langle yz\rangle=0.1\sigma_y\sigma_z$.
- No large emittance growth for the tune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





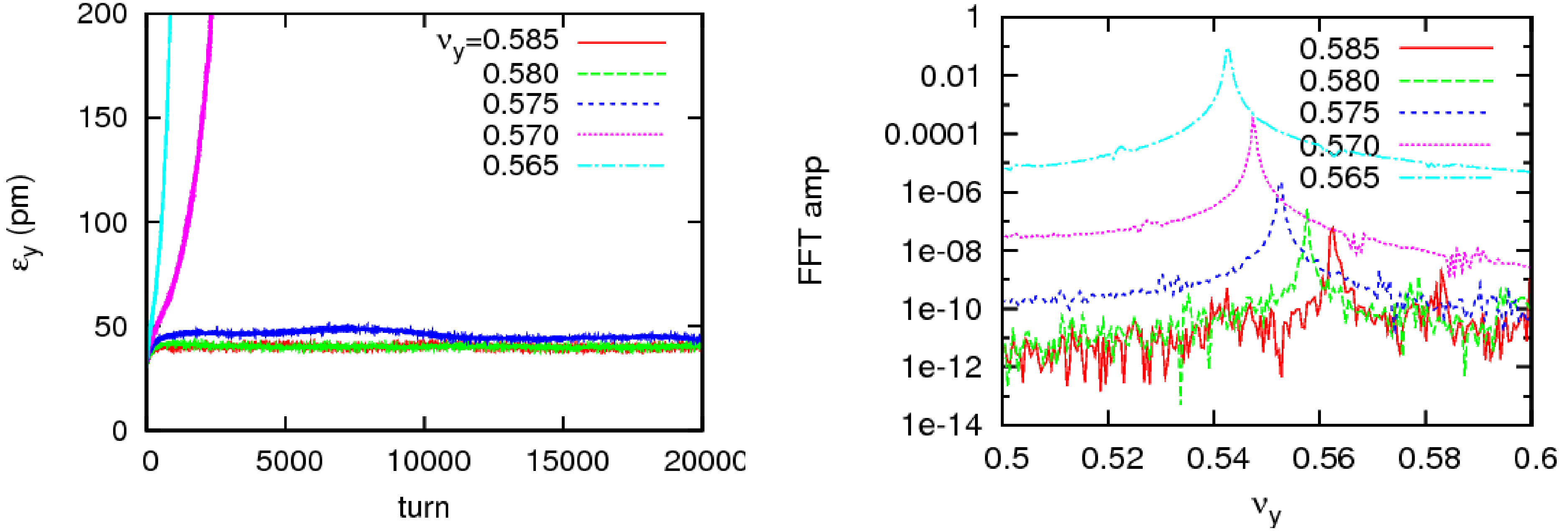






BxB feedback ON with collimator offset 1mm

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

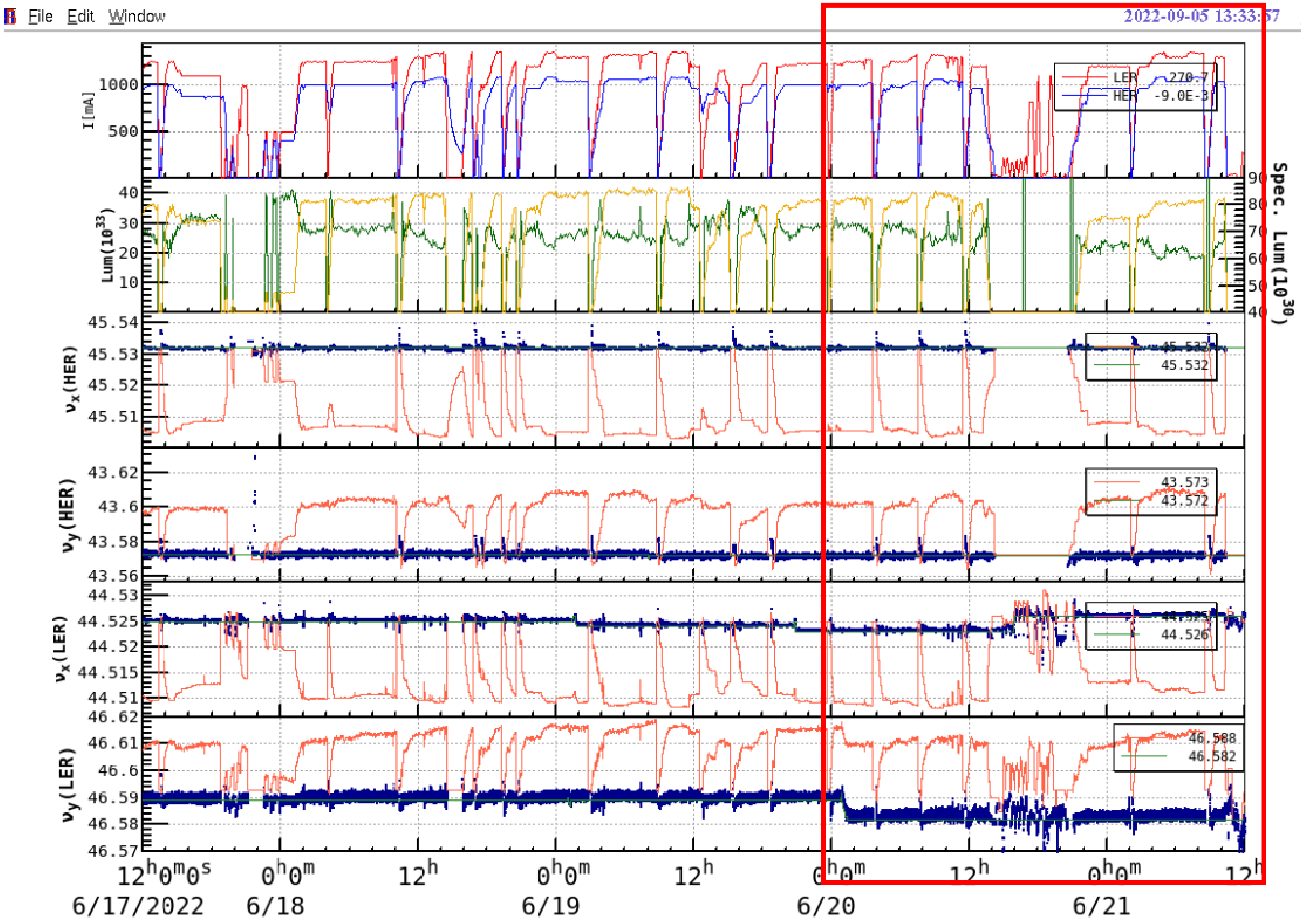


- No remarkable change from the case without collimator offset.

Summary

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



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

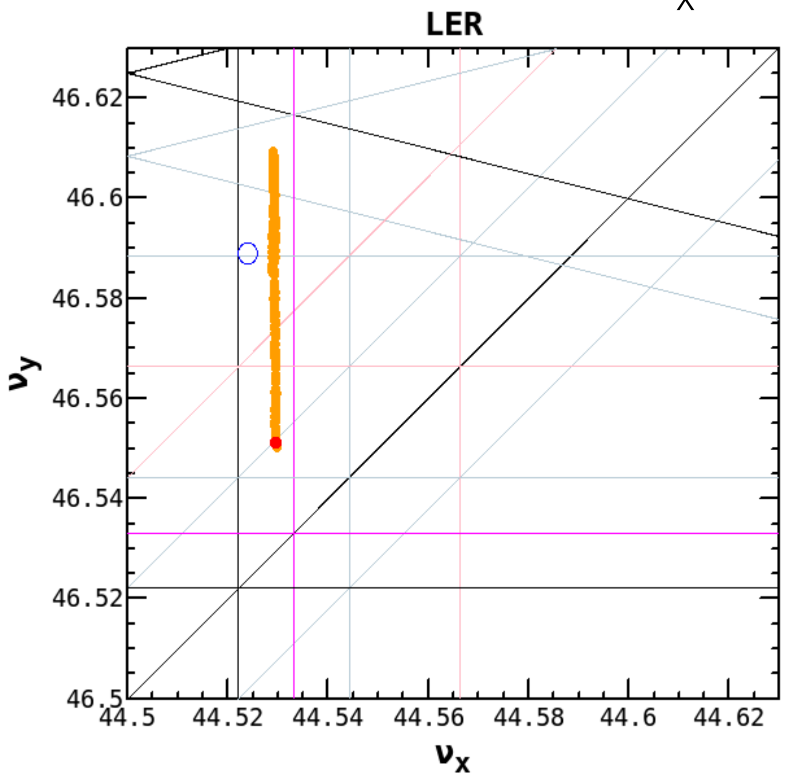
Thank you for your attention

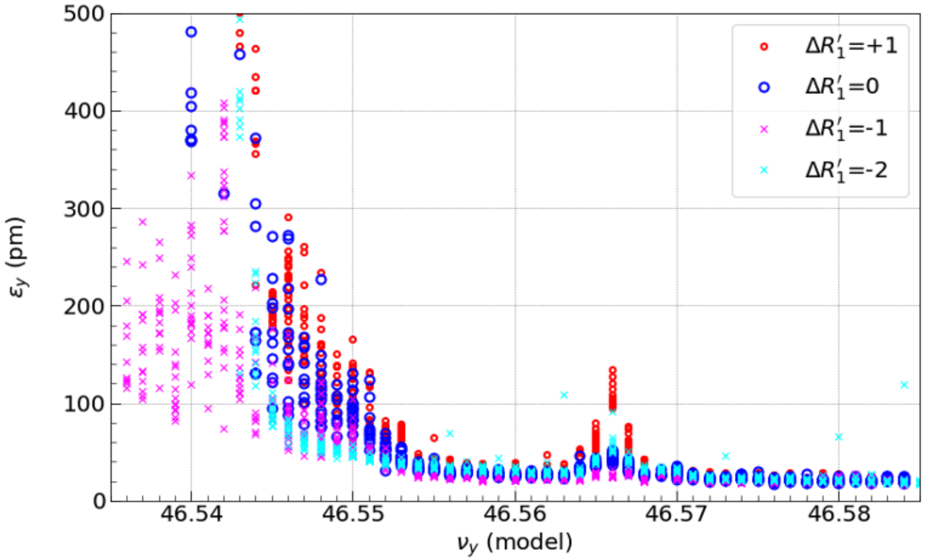
Vertical Beam size vs ν_y at by*=1mm (Dec. 2021)

No collision

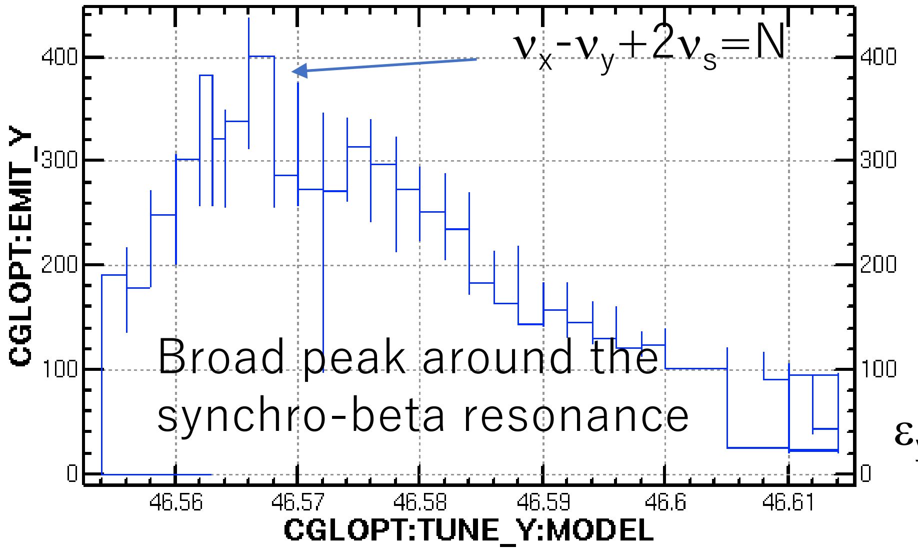
$k\beta=36.1\times10^{15}$ V/C

$\nu_x = 0.529$





I=0.10mA/b



$\nu_x-\nu_y+2\nu_s=N$

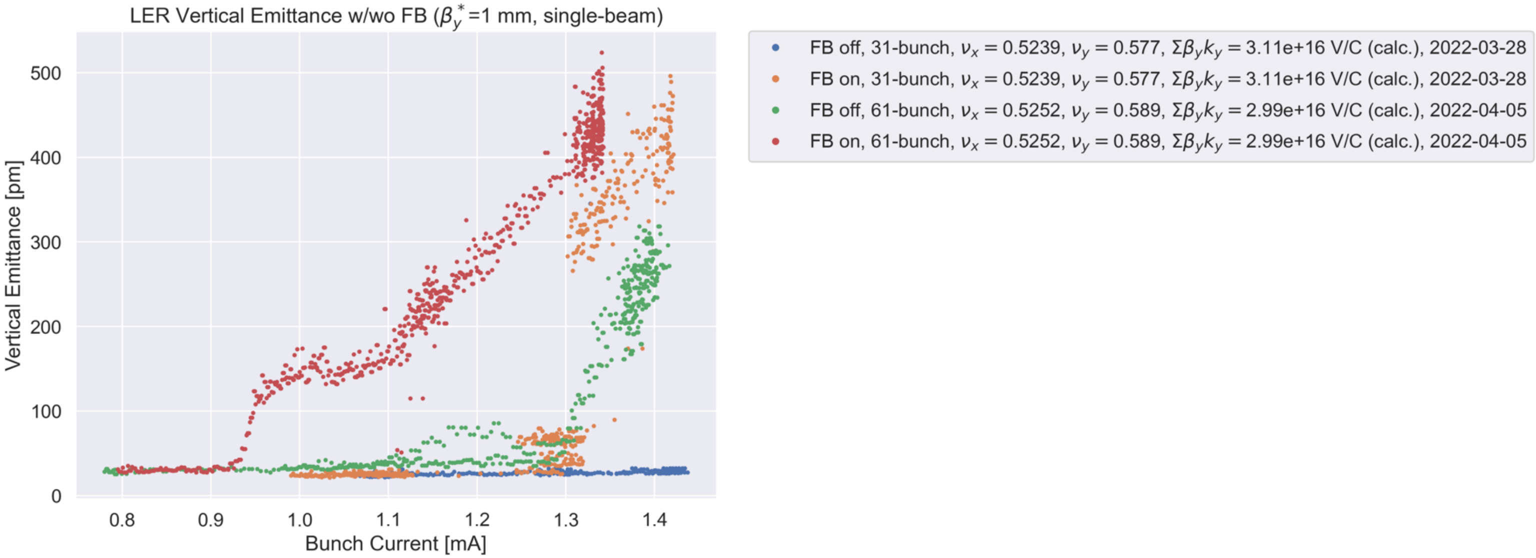
Broad peak around the synchro-beta resonance

I=0.90mA/b

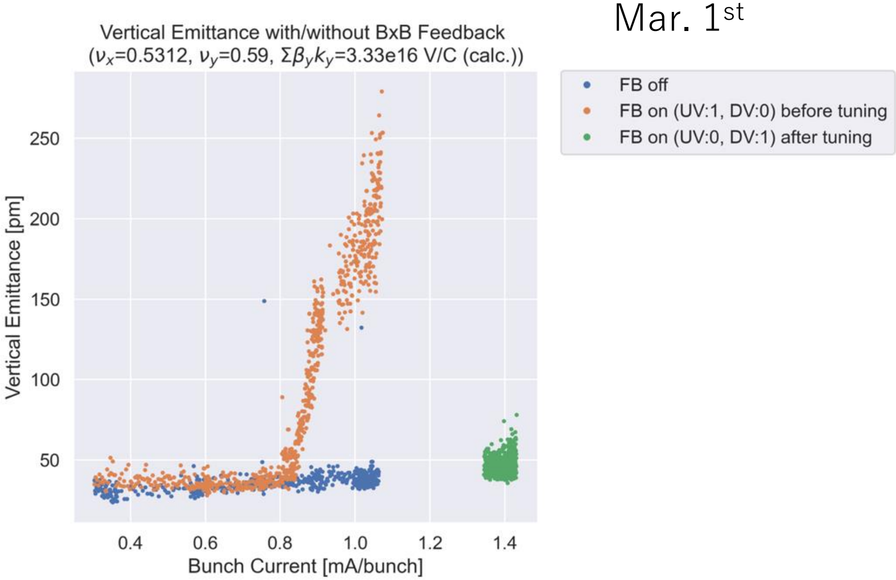
$\varepsilon_y\sim20$pm@$\nu_y=0.61$

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



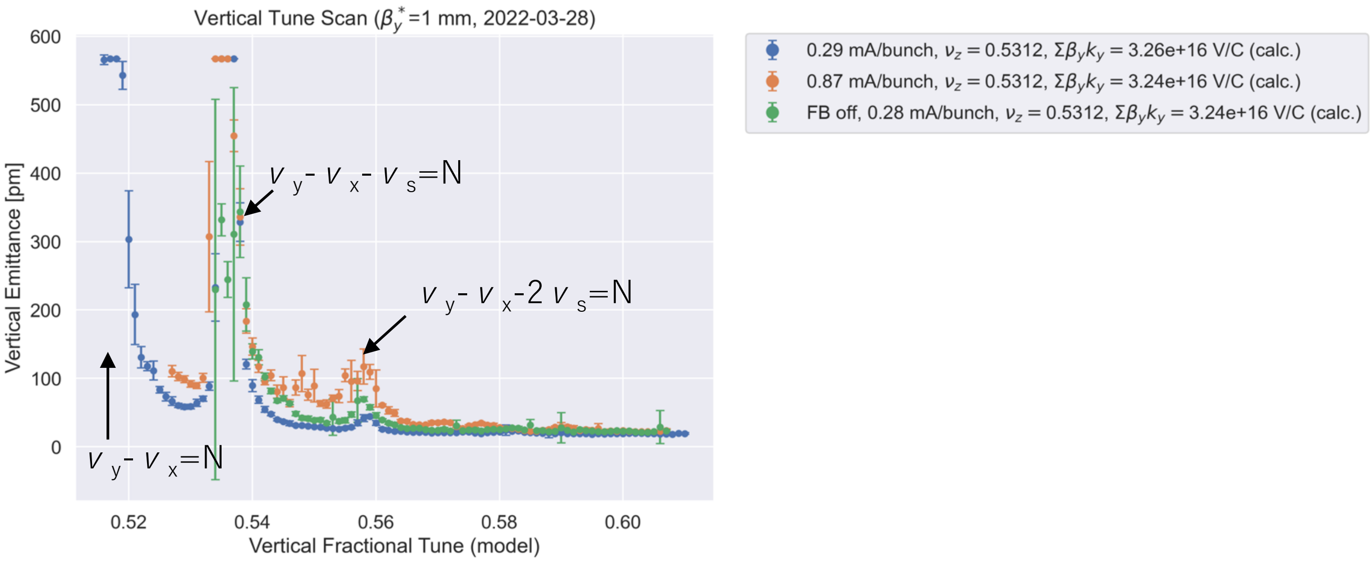
✓ Two FB loops were tuned to suppress the betatron frequency and the number of taps was reduced.

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

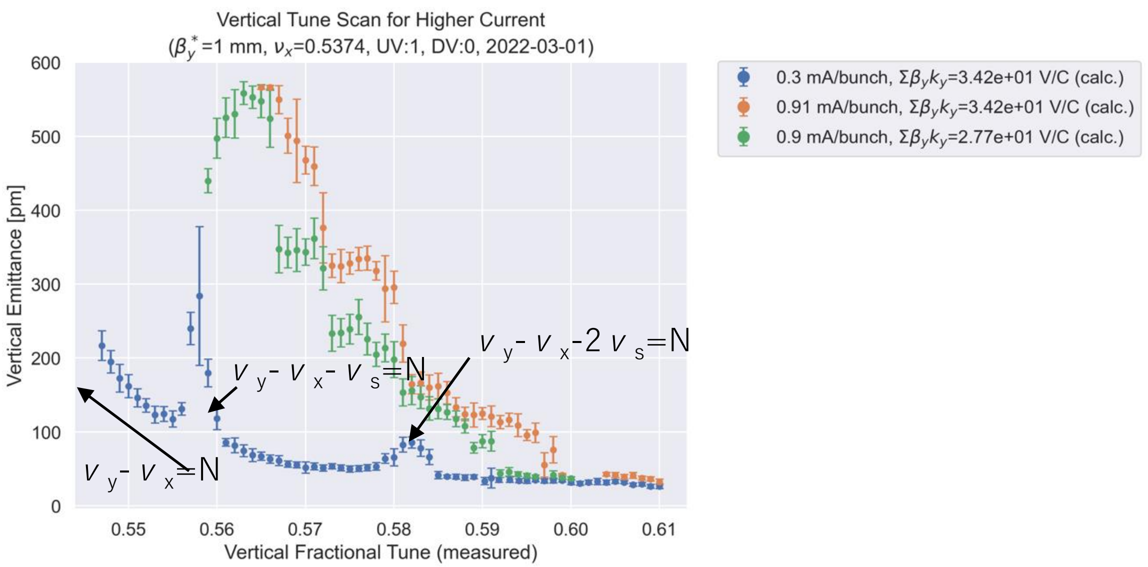
Tune Survey

- 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)



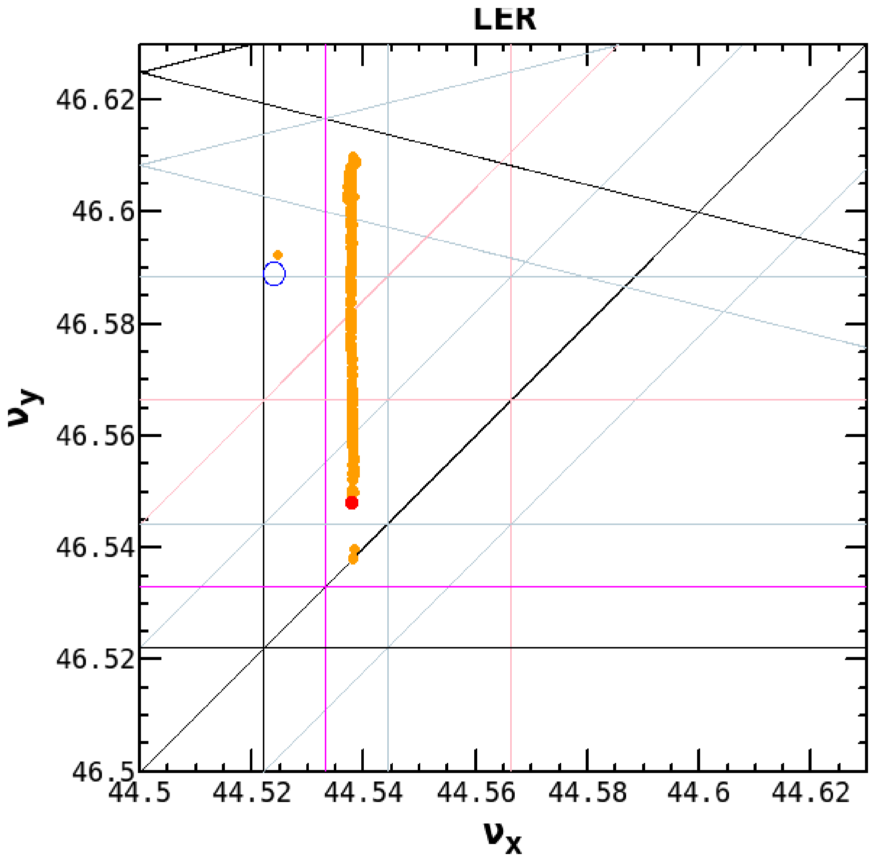
2022-03-01 (97-bunch)

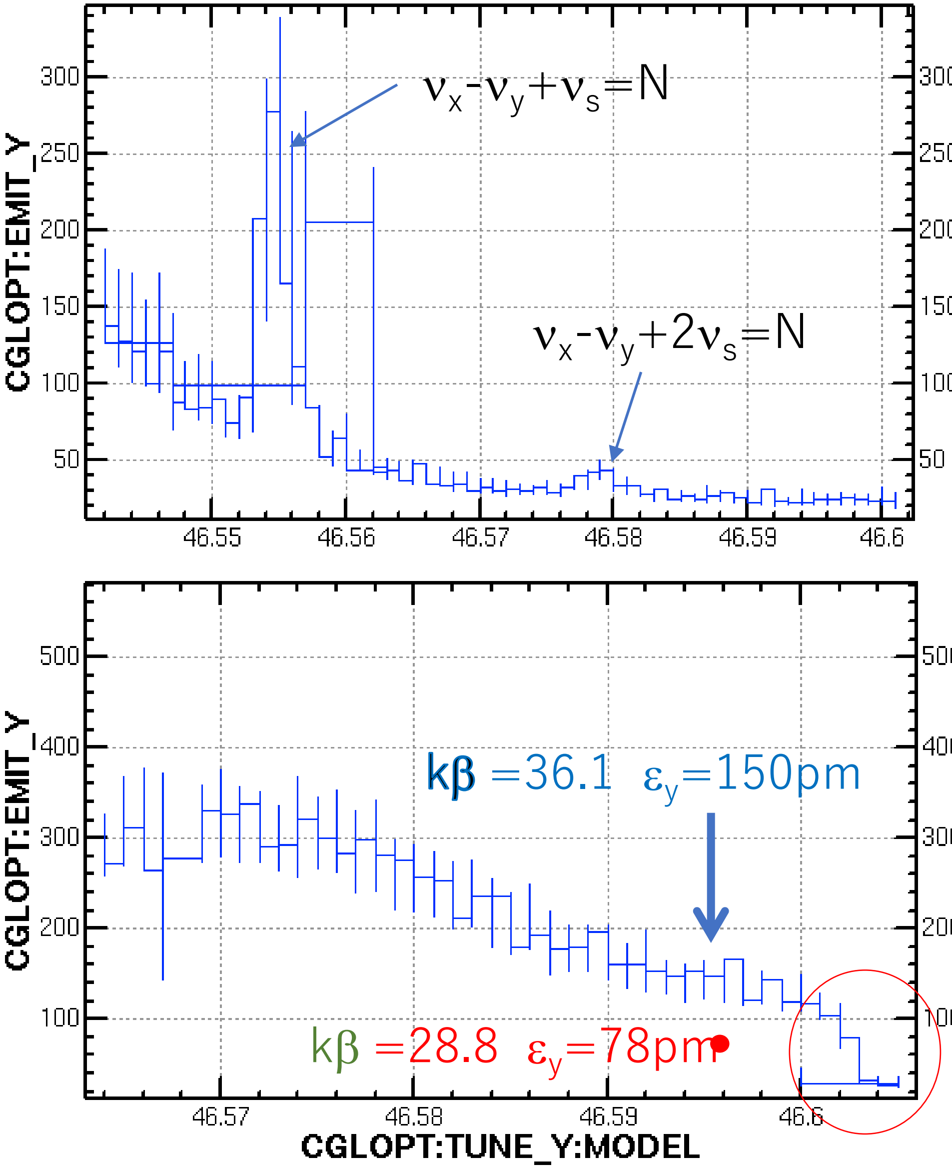


Vertical Beam size vs ν_y at $\nu_x = 0.538$

No collision

$k\beta = 36.1 \times 10^{15}$ V/C





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

I=0.30mA/b

I=0.90mA/b

Injection difficult 0.7mA/b at $\nu_y = 0.6$

V Emittance depends on the impedance.

Feedback system for a naive idea

- Betatron oscillation, $(X+iP)_n = e^{-in\mu}(X+iP)_0$ $\quad X = \dfrac{y}{\sqrt{\beta_y}} \quad P = \dfrac{\alpha_y y + \beta_y y'}{\sqrt{\beta_y}}$
  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

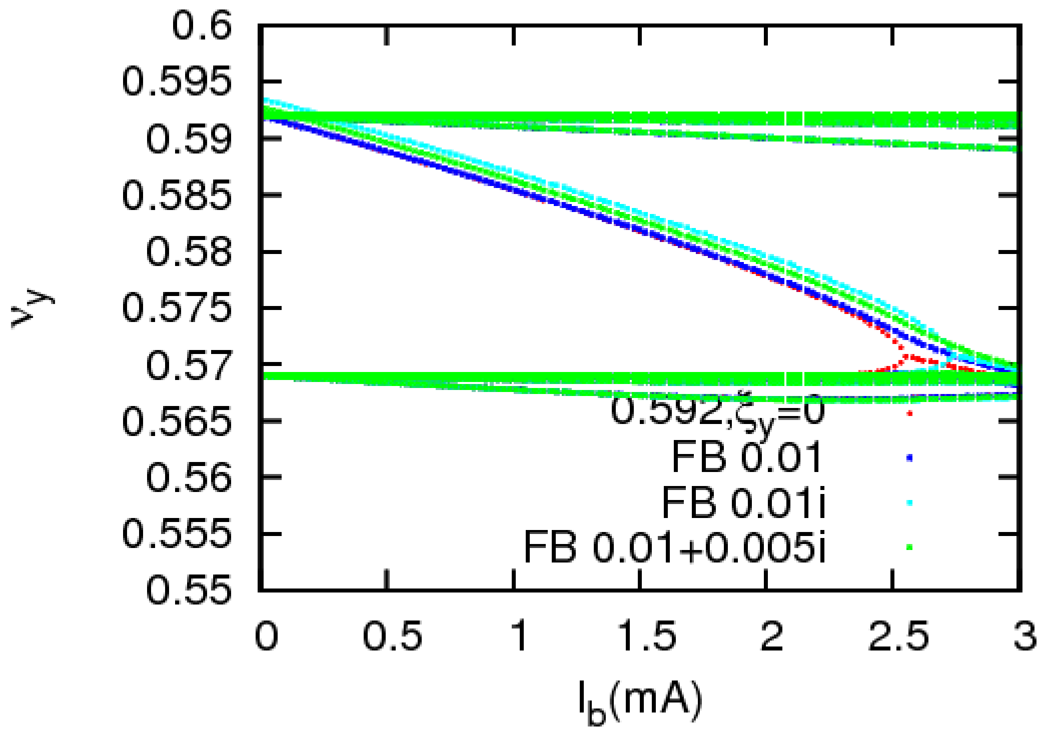
$$X_K = \frac{2}{N_{tap}}\sum_{n=0}^{(N_{tap}-1)} X_n \cos(n\mu + \Delta\phi)$$

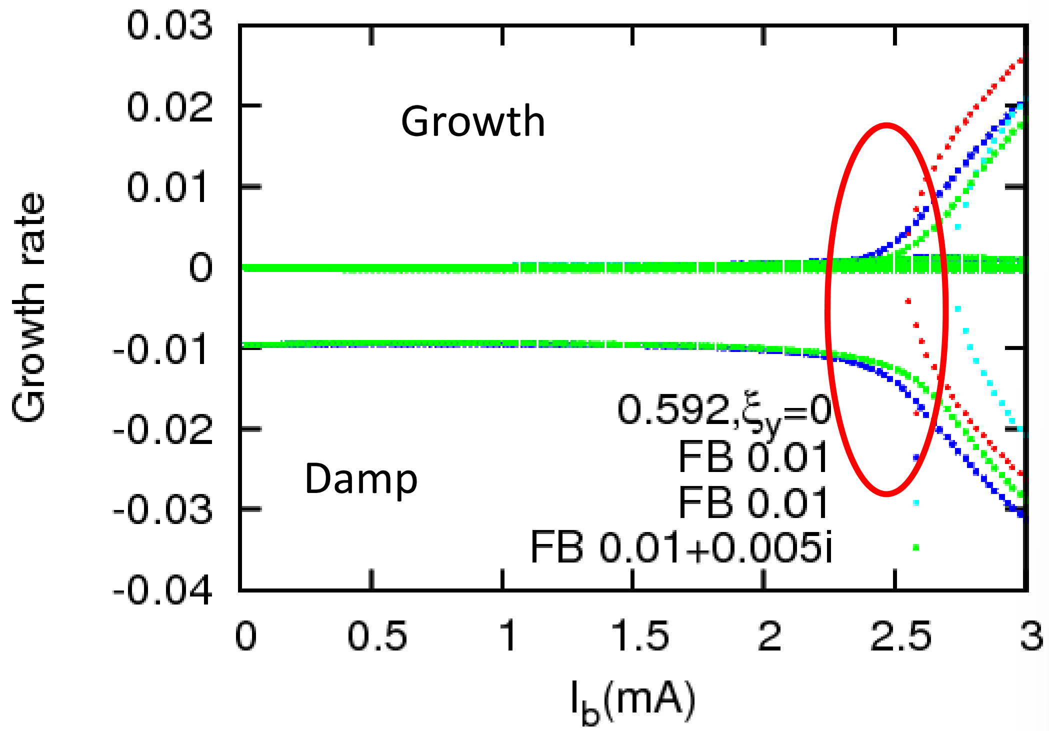
$$\Delta P = -2bX_K$$

Mode analysis for zero chromaticity

[K. Ohmi]

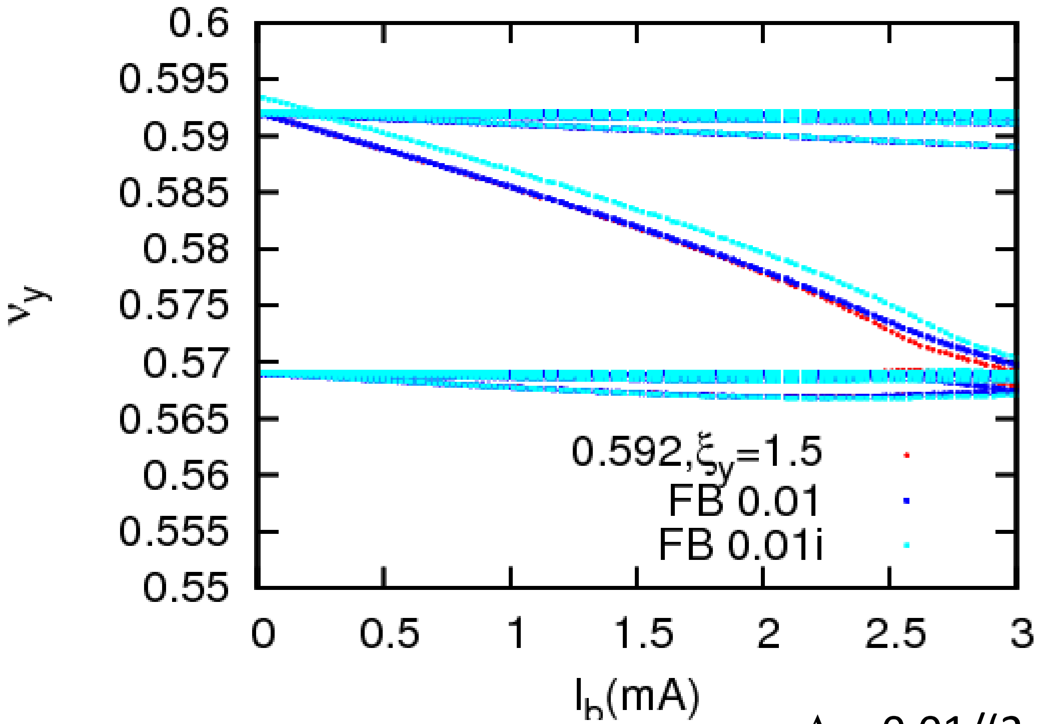
- At zero chromaticity, imaginary part of tune apprear blow the TMCI threshold as is demonstrated by E. Metral.
- The strength seems weak.

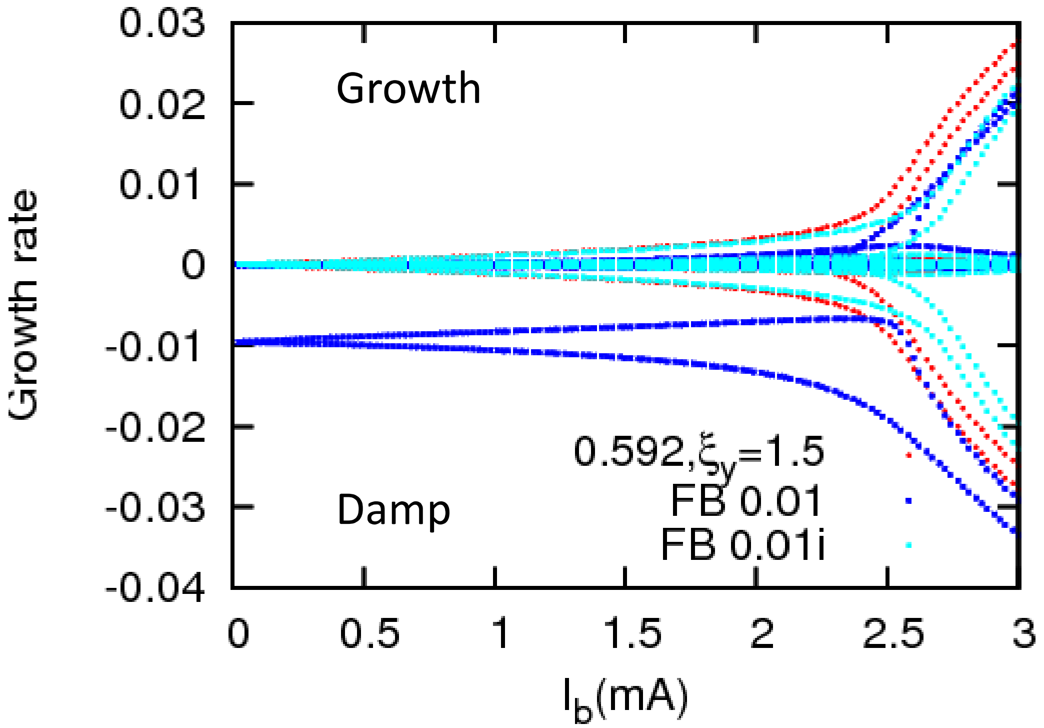




Mode analysis for ξ_y=1.5

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





$\Delta\nu$=0.01/(2π)~0.0017

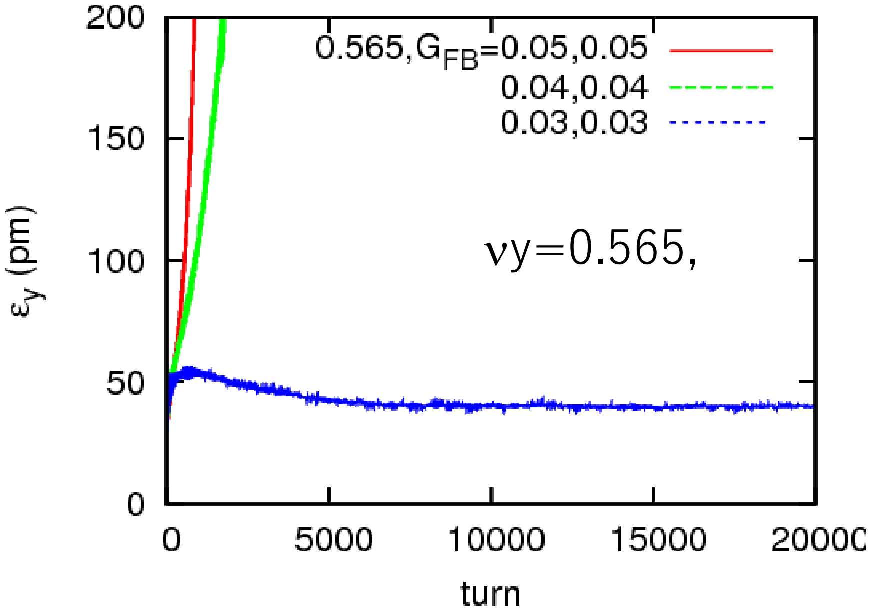
[K. Ohmi]

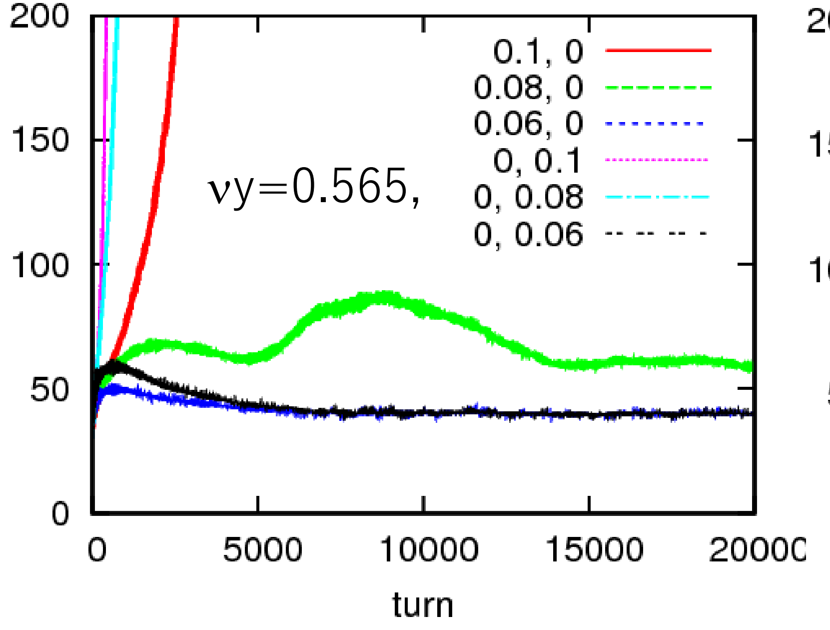
Bunch oscillation mode affected by BxB feedback

- 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.

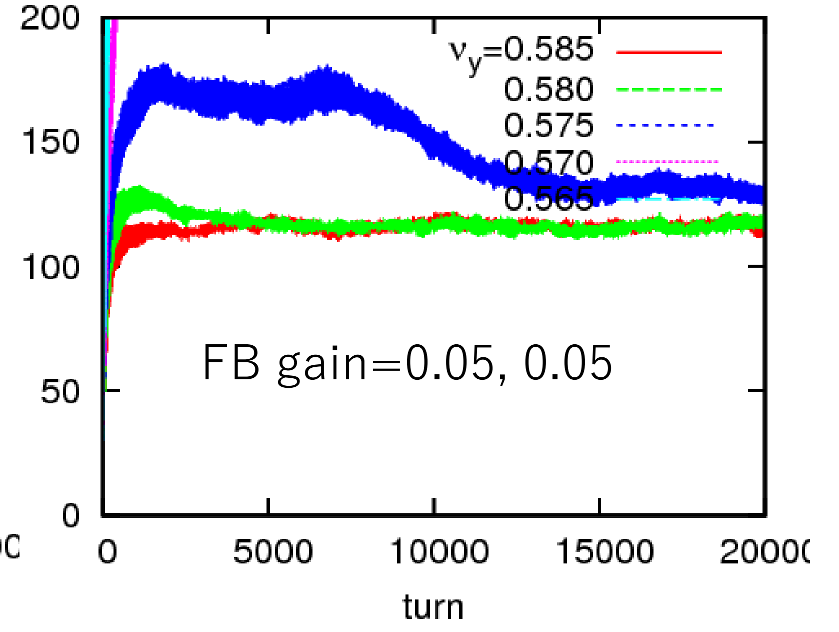
FB gain and collimator offset

FB Gain scan for yw=1mm



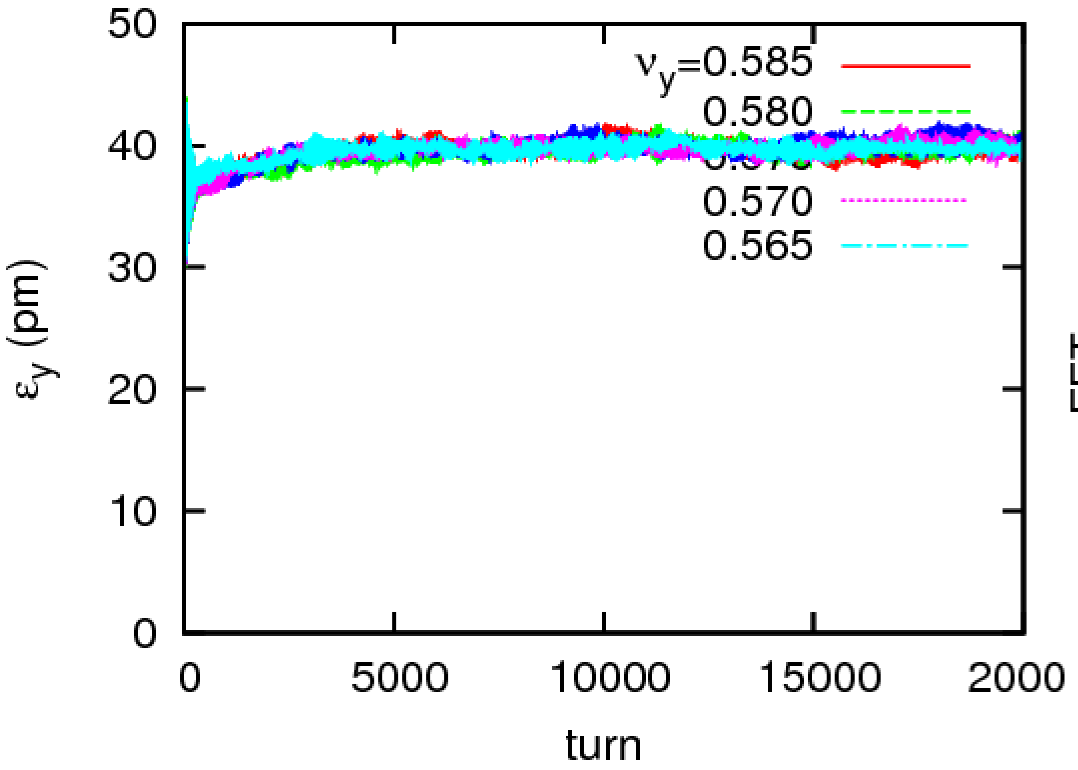


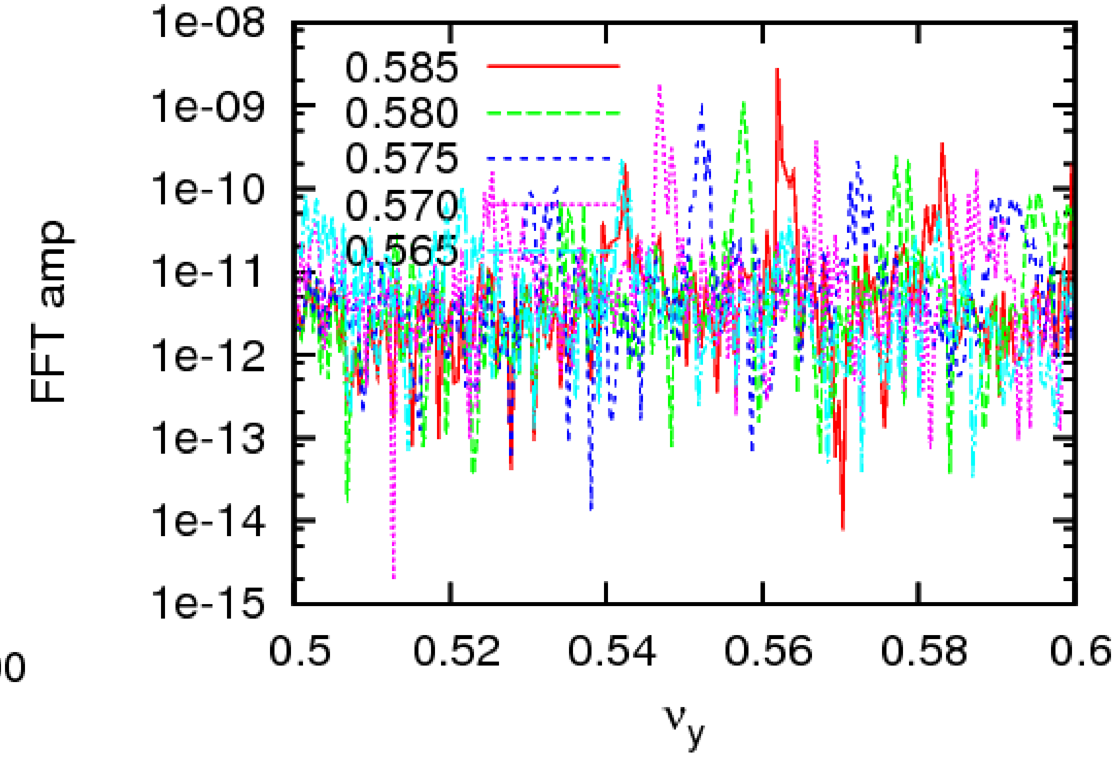
tune scan for yw=3mm



1 tap resistive feedback

- Simplest feedback model
- Use 2nd feedback loop, FB gain 0.1. No growth at G=0.15.
- Choose $\phi(K2) = \phi(M1) + 0.25 - \nu_y(0.585)$.
- -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
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Katsunobu Oide
Kazuhito Ohmi
Kazuro Furukawa
Keisuke Yoshihara
Makoto Tobiyama
Mauro Migliorati
Mika Masuzawa
Mikhail Zobov
Andrii Natochii
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

- 4^{th} (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
- 3^{rd} (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
- 2^{nd} (https://kds.kek.jp/event/39472/)
  - Machine study items and so on, T. Ishibashi
  - Impedance calculations of collimators with simple geometries, D. Zhou
- 1^{st} (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