TMCInstability influence on SuperKEKB luminosity

K. Ohmi (KEK)

The 2021 International Workshop on the High Energy Circular Electron Positron Collider

Thanks to H. Fukuma, T. Ishibashi, G. Mitsuka, S. Terui, D. Zhou

Observations in SuperKEKB-LER

- Vertical Beam size blowup has been observed near the tune operating point of physics run ν_y<0.6 in SuperKEKB-LER.
- It is a single bunch effect. The threshold is lower than that of the ordinary TMCI. The blowup is related to a resonance $\nu_x - \nu_y + 2\nu_s$.
- Increasing the bunch intensity and/or transverse impedance (collimator aperture) enhanced the blowup.
- The beam size blow-up limits choice of the operating point in Physics run.

Phenomena caused by Transverse wake force

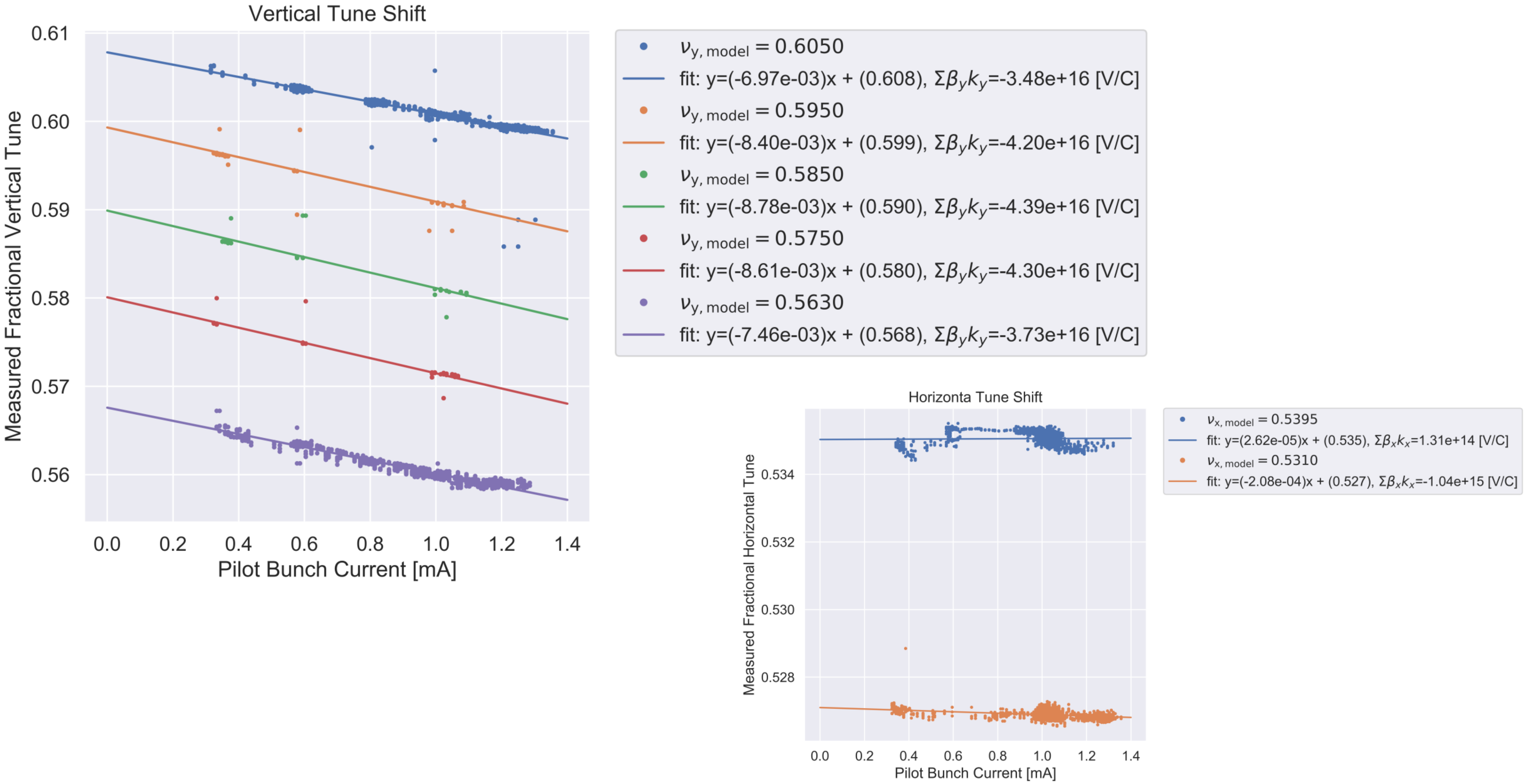
- Tune shift
  - Dipole mode tune shift $\rho_x(z) = x\rho(z)$
- Transverse mode coupling
  - Mode coupling between $\nu_y \pm n\nu_s$ and $\nu_y \pm (n+1)\nu_s$. Typically ν_y and $\nu_y - \nu_s$. The threshold depends on ν_s but does not depends on ν_y.
  - For localized wake, mode tune is wrapped at 0.5. Complex condition for the mode coupling $\nu_y \pm \mathrm{n}\nu_s \pm \nu_y \pm \mathrm{m}\nu_s$ =integer. The condition is the same as half integer resonances for synchro-beta mode.
  - Bunch current dependent phenomena.

Tune shift Measurements

	Vertical					Horizontal					
date	βK(V/C, calc)	βK (dν/dI)	dν/dI (mA^{-1})	ν_0	$\Delta\beta$K	βK(V/C, calc)	βK (dν/dI)	dν/dI (mA^{-1})	ν_0	$\Delta\beta$K	$\Delta\xi_y$
2021/2/25	8.90E+15	1.81E+16	-0.00363	0.587	9.24E+15	3.90E+15	6.49E+15	-0.0013	0.528	2.59E+15	
2021/2/25	2.66E+16	3.08E+16	-0.00617	0.586	4.23E+15	3.90E+15	-6.29E+15	0.00126	0.528	-1.02E+16	
2021/2/25	3.71E+16	3.63E+16	-0.00727	0.586	-7.79E+14	3.90E+15	5.95E+15	-0.00119	0.528	2.05E+15	
2021/2/25	5.99E+16	5.70E+16	-0.0114	0.6	-2.95E+15	3.90E+15	5.75E+15	-0.00115	0.527	1.85E+15	+2
2021/3/1	4.83E+16	4.94E+16	-0.00989	0.587	1.11E+15	3.90E+15	6.59E+15	-0.00132	0.527	2.69E+15	
2021/3/1	4.83E+16	4.99E+16	-0.00999	0.587	1.61E+15	3.90E+15	6.79E+15	-0.00136	0.527	2.89E+15	+1
2021/3/1	4.83E+16	5.50E+16	-0.011	0.565	6.66E+15	3.90E+15	8.84E+15	-0.00177	0.527	4.94E+15	+1

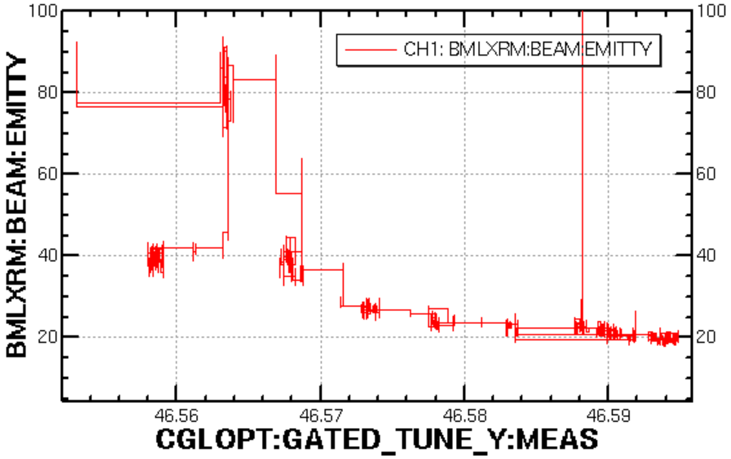
Base chromaticity ξ_y=1.6

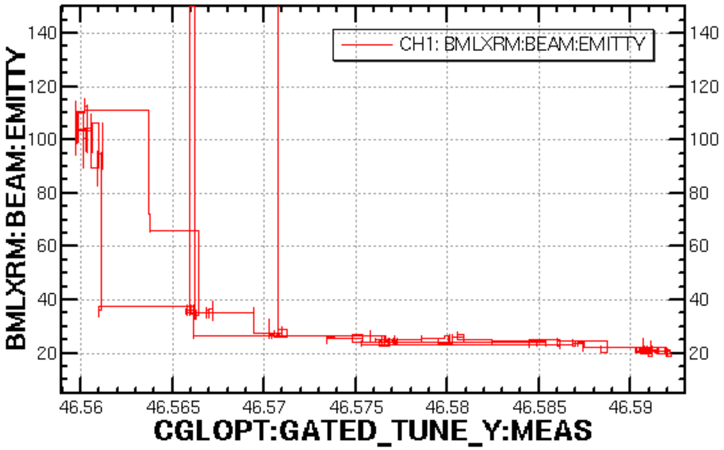
Tune shift measurement with pilot bunch



ε_y vs ν_y at Kβ=36x10^{15} V/C (June 29), β_y*=1mm

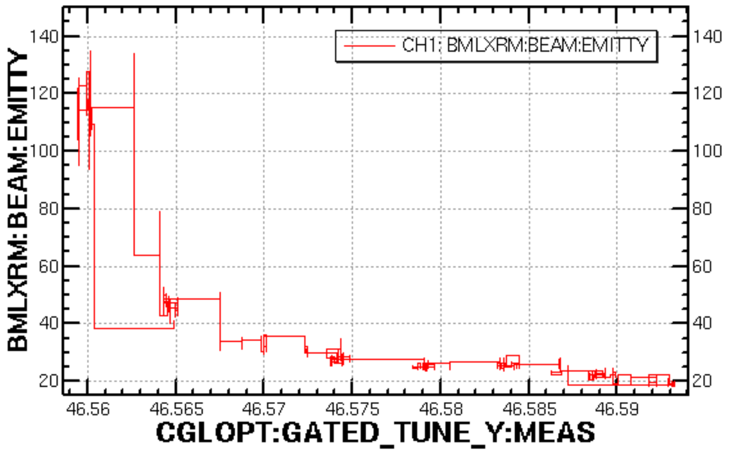
- 0.5mA/b (16:10-16:30)   0.7mA(16:55-17:05)

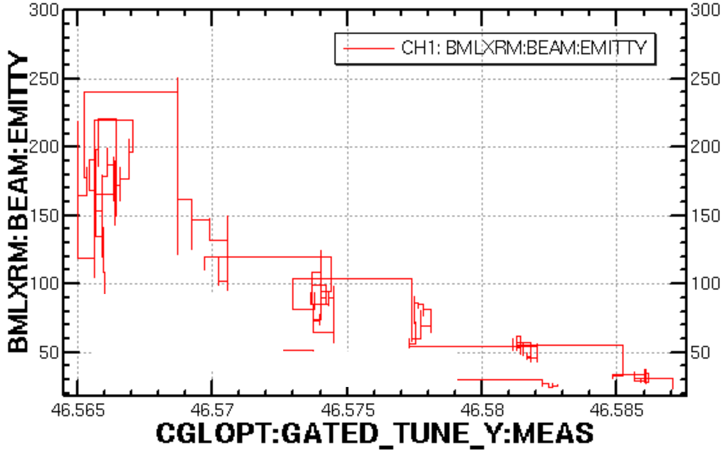




- Emittance growth due to current independent resonance (nx-ny-2ns or 2ny-6ns=n) for I=<0.8mA/bunch.
- Emittance growth due to tune dependent TMCI (localized wake) was seen I>=0.9mA
- ε_y=150pm at I=1mA ν_y=0.588
- I_{th}=0.95mA at Kb= 36x10^{15} V/C.

- 0.8mA (17:05-17:15)   0.9mA (17:20-17:28)



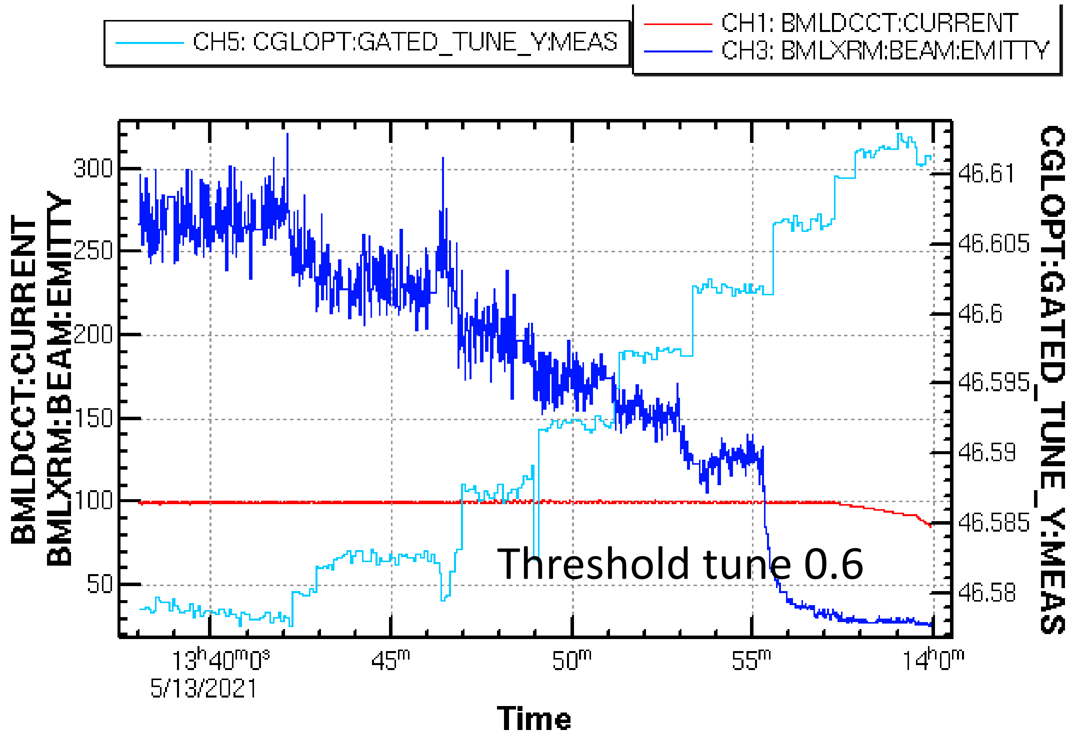


LER measurement at May 13, $\beta_y^*=1\mathrm{mm}$

$d\nu_y/dI=0.008/\mathrm{mA}$

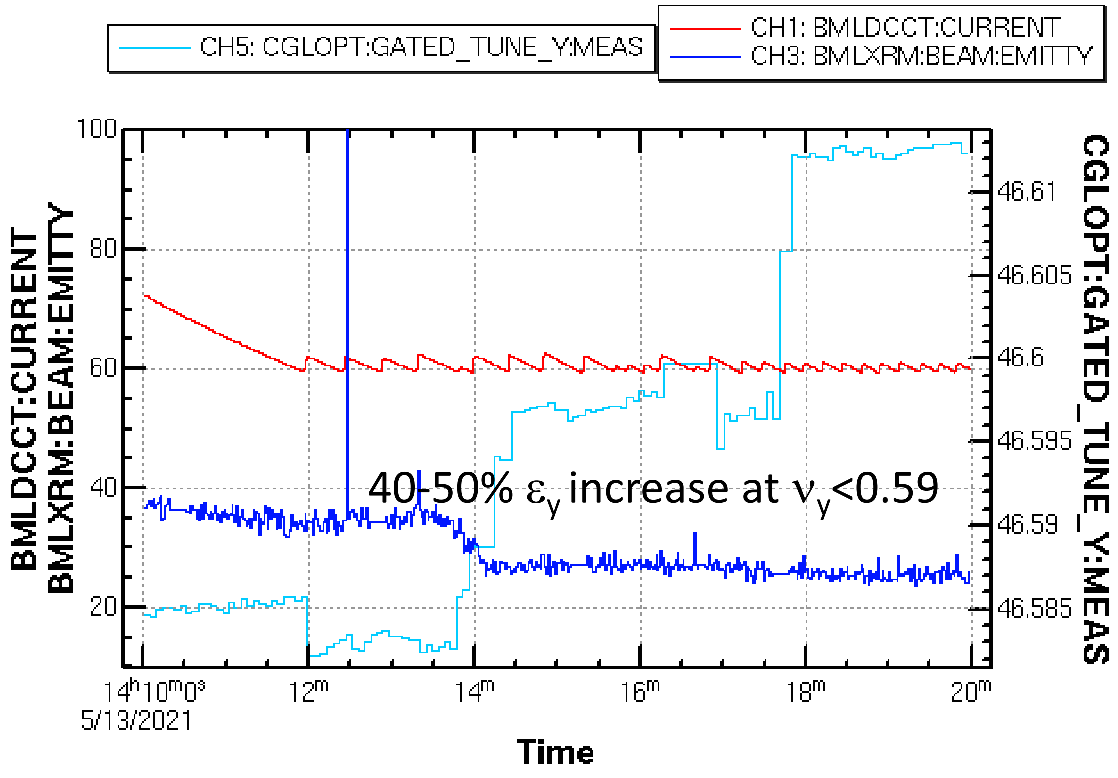
- Keep current scan V-tune 0.570-0.610

1mA/bunch



Threshold tune 0.6

0.6mA



40-50% ε_y increase at $\nu_y<0.59$

BOR data taking

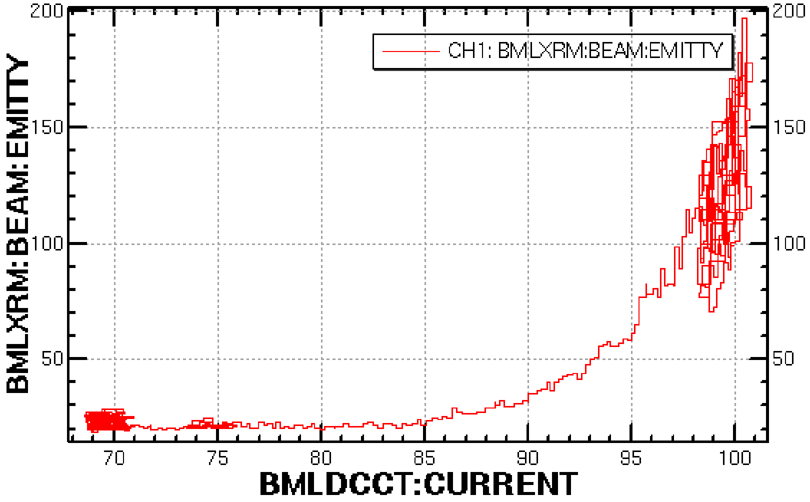
Emittance blow up was seen at 1mA/bunch.

Threshold change for Collimator gap

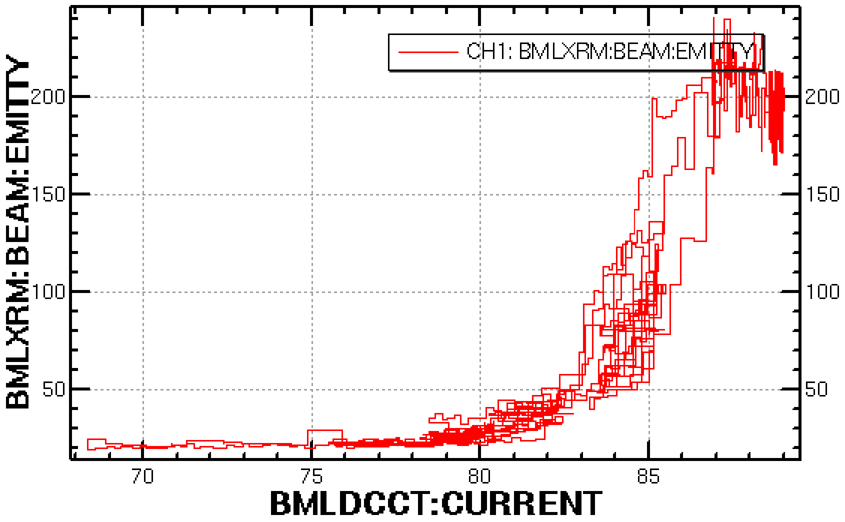
$\beta_y^*=1\text{mm}$

$\nu_y=0.59$

$K\beta=36\text{x}10^{15}$ V/c



$K\beta=41.6\text{x}10^{15}$ V/c



97bunch

- The threshold almost scales to KβI.
- The emittance growth seems to be due to TMCI, though not ordinary TMCI.

FFT spectra of BOR data

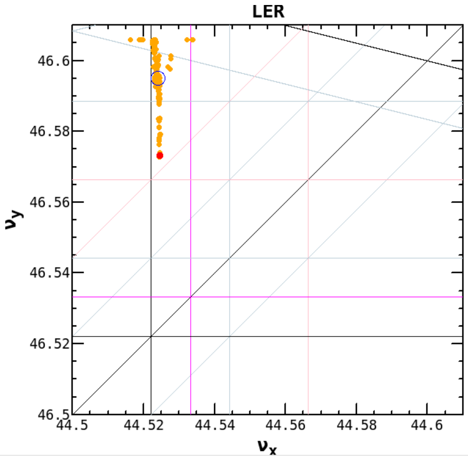
β_y^*=1mm

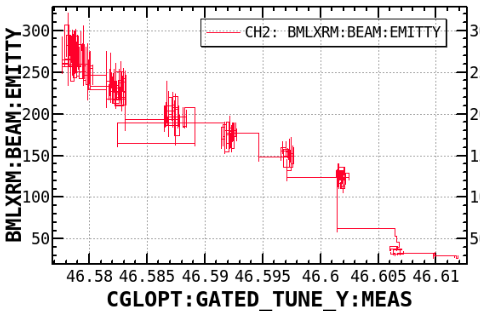
- Take FFT all 5120x4096 data.
- Averaging revolution periods with the weakest 300 (in 5120) FFT power.

I=100mA, Nb=97

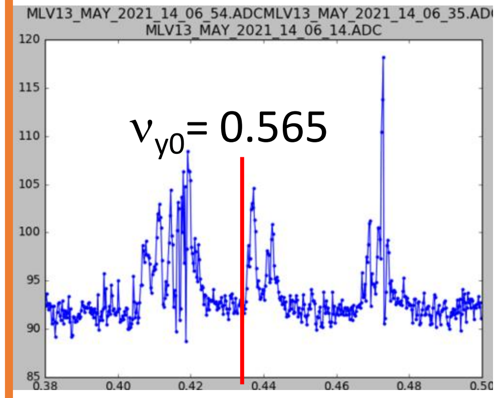
ν_s(LER)=0.0225

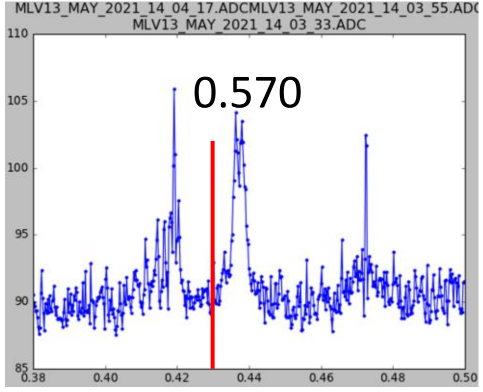
$d\nu_y/dI$=0.008/mA

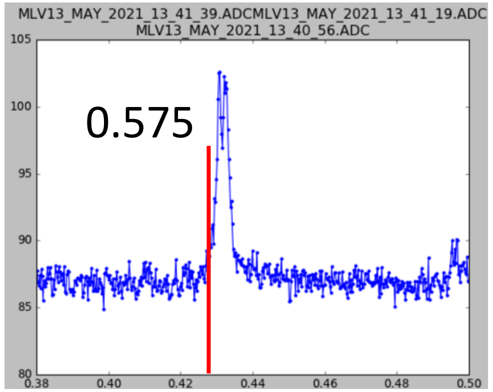


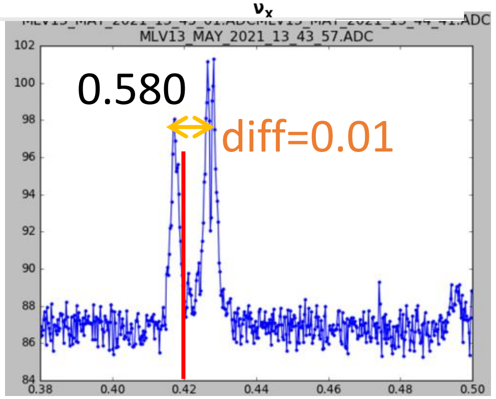


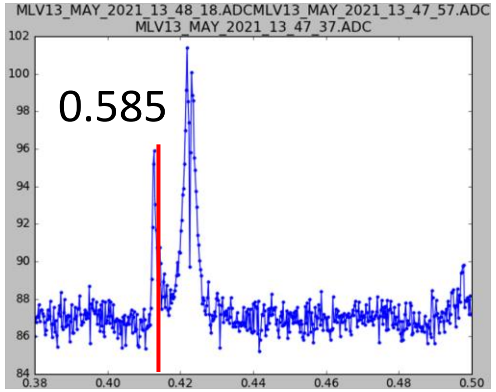
Near resonance lines $\nu_x - \nu_y + 2\nu_s$ and $2\nu_y - 6\nu_s$

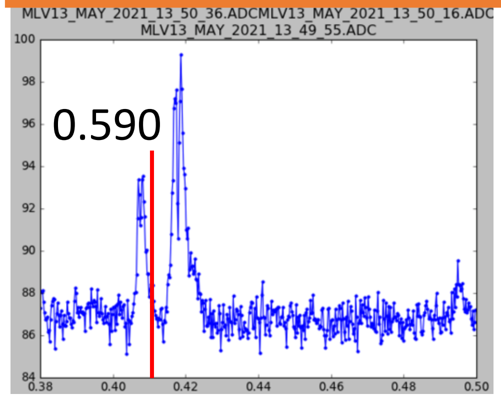


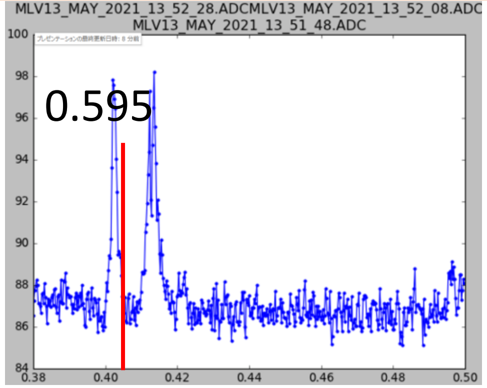


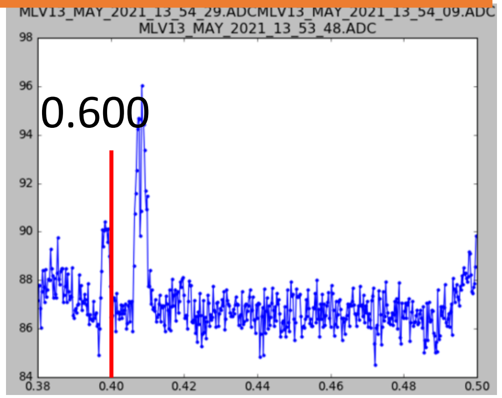


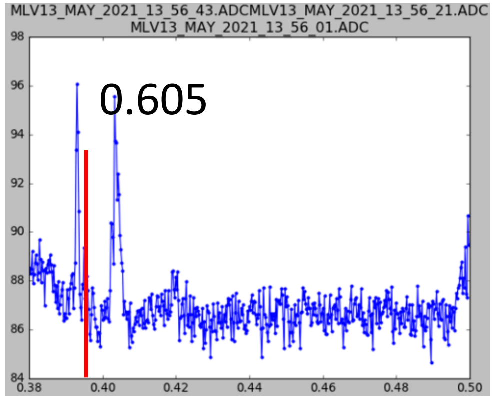


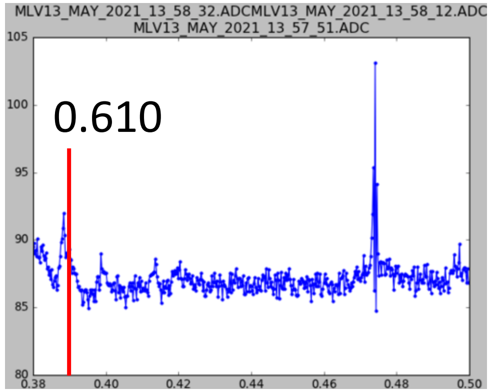








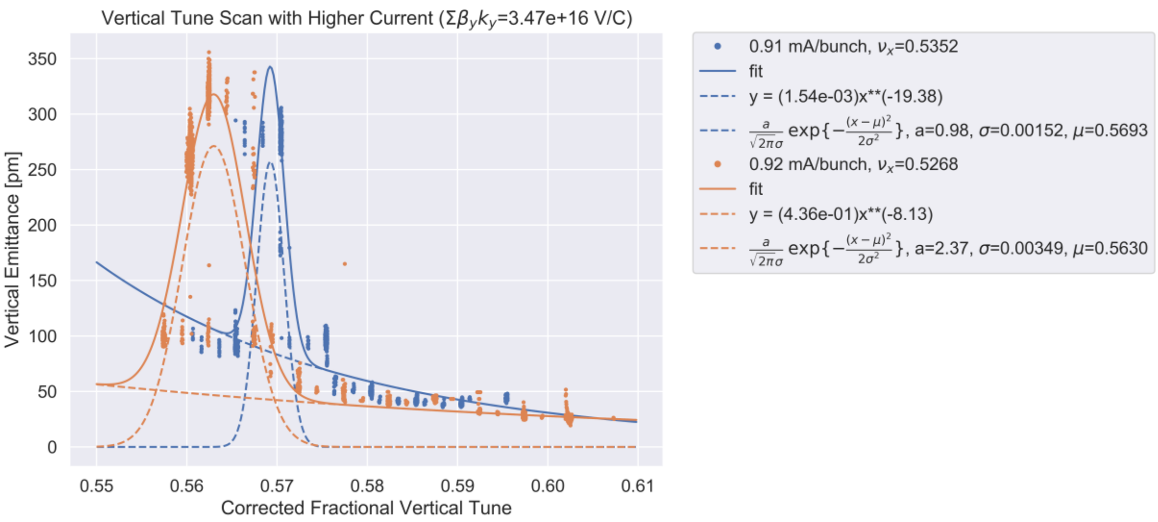




Spectra ν_y ≥0.58 seems ordinary behavior, still the tune separation remains 0.01 for the mode coupling.

Spectra ν_y <0.58 is complex, perhaps coupling with $\nu_x - \nu_y + 2\nu_s$resonance.

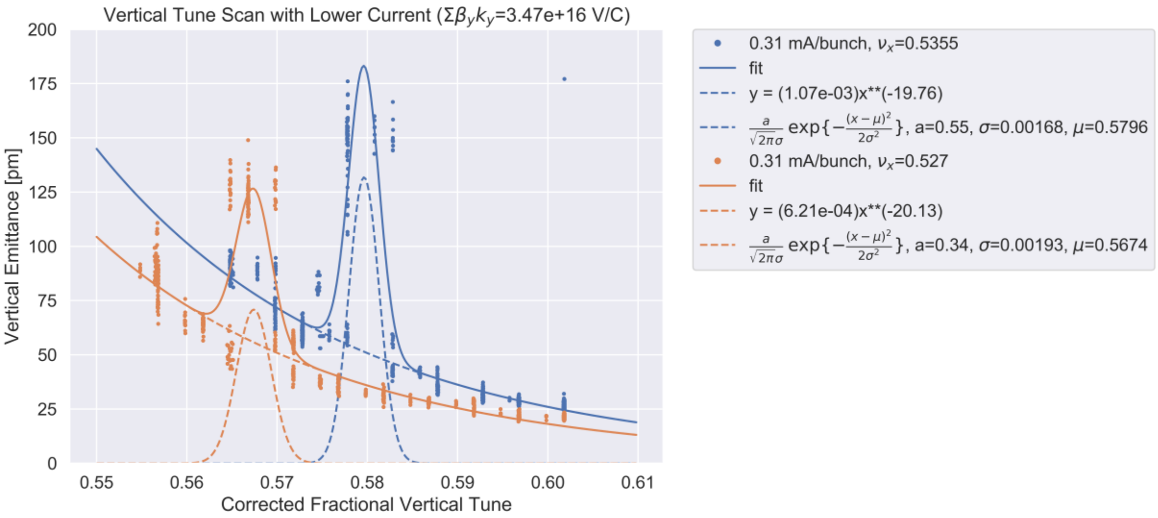
Tune scan (corrected tune) at β_y*=8mm

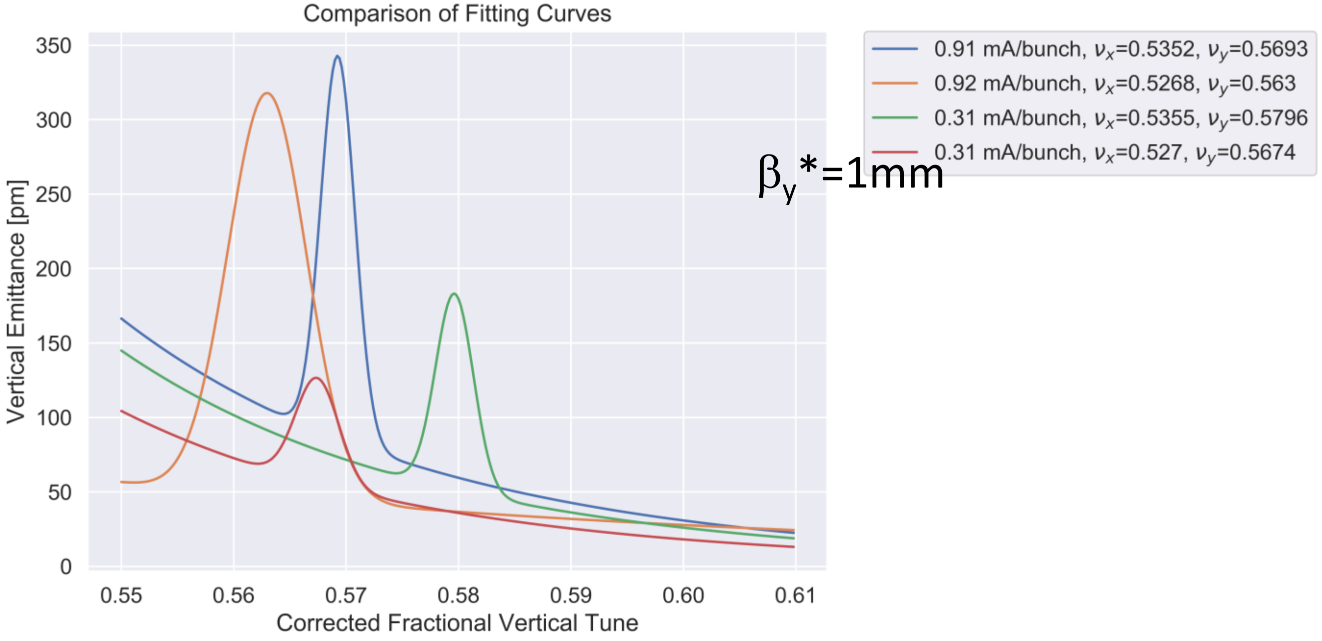


- The corrected tunes mean evaluated tunes using results of the tune shift measurement and averaged bunch current because the bunch current between the pilot bunch and the other bunches is different.

$$\nu_y = -7.21\text{e-}3 \times I_{b,ave} + (\nu_{y,model}+0.004)$$

$I_{b,ave}$: averaged bunch current

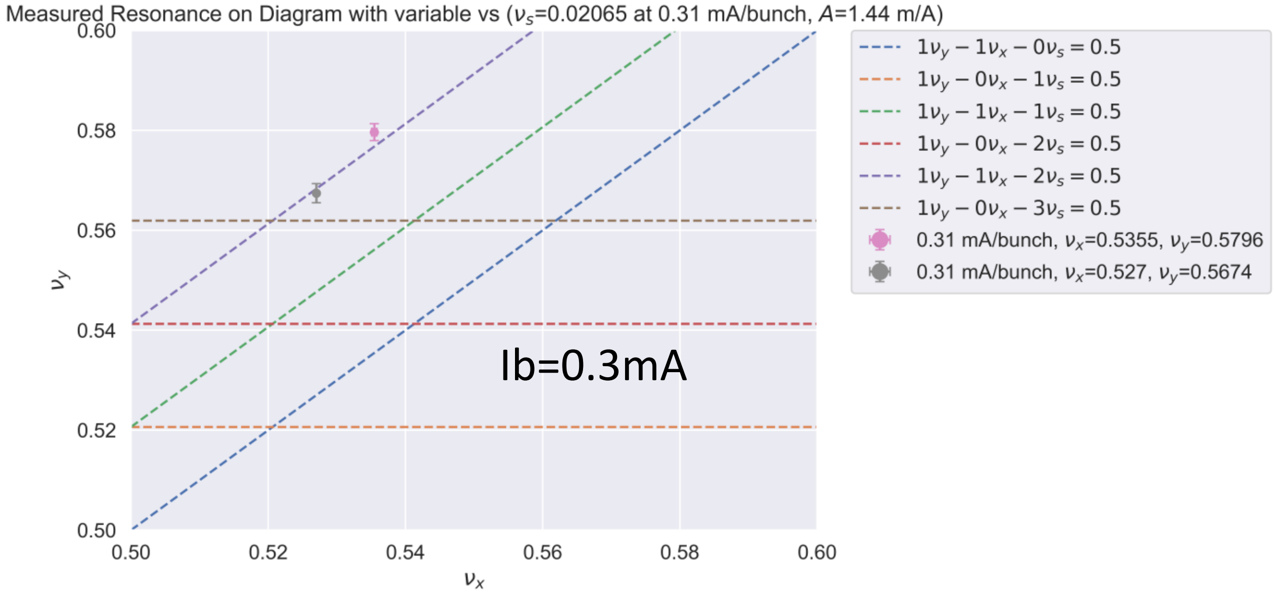




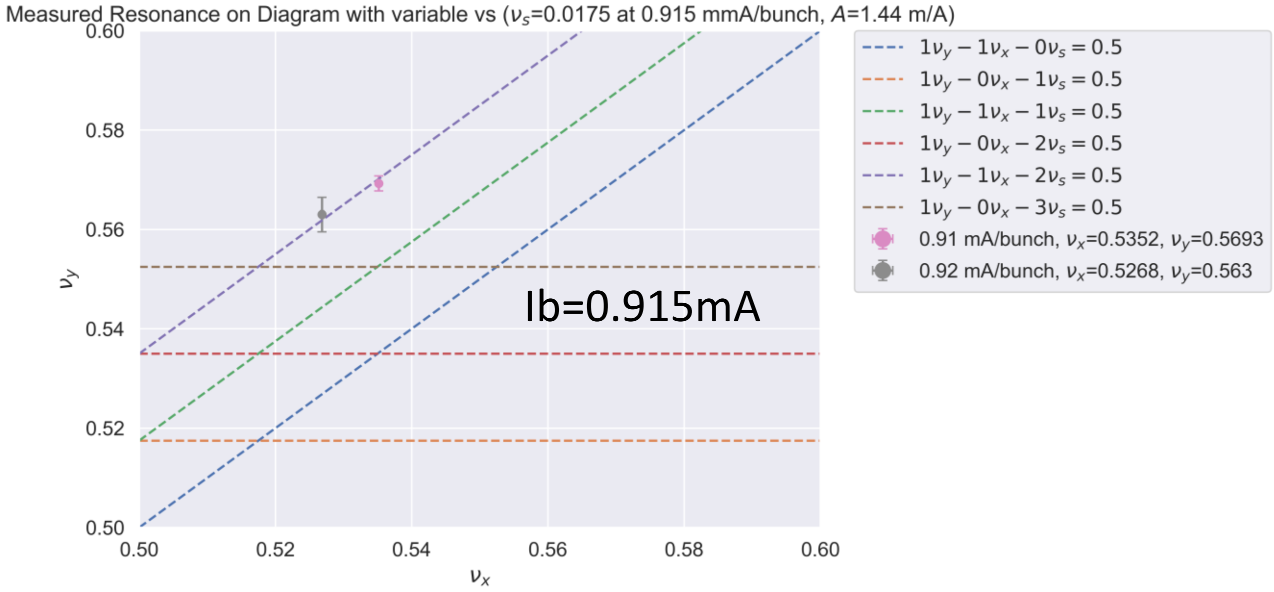
β_y*=1mm

Resonance on tune diagram (variable ν_s)

β_y*=8mm


Measured Resonance on Diagram with variable vs (ν_s=0.02065 at 0.31 mA/bunch, A=1.44 m/A)

Ib=0.3mA


Measured Resonance on Diagram with variable vs (ν_s=0.0175 at 0.915 mmA/bunch, A=1.44 m/A)

Ib=0.915mA

- Estimate the synchrotron tune shift by the bunch lengthening using parameters of the model lattice.

$$\nu_s = \frac{C\alpha_c\sigma_\delta}{2\pi\sigma_z}$$

$$\sigma_z = \sigma_{z0} + A\, I_b$$

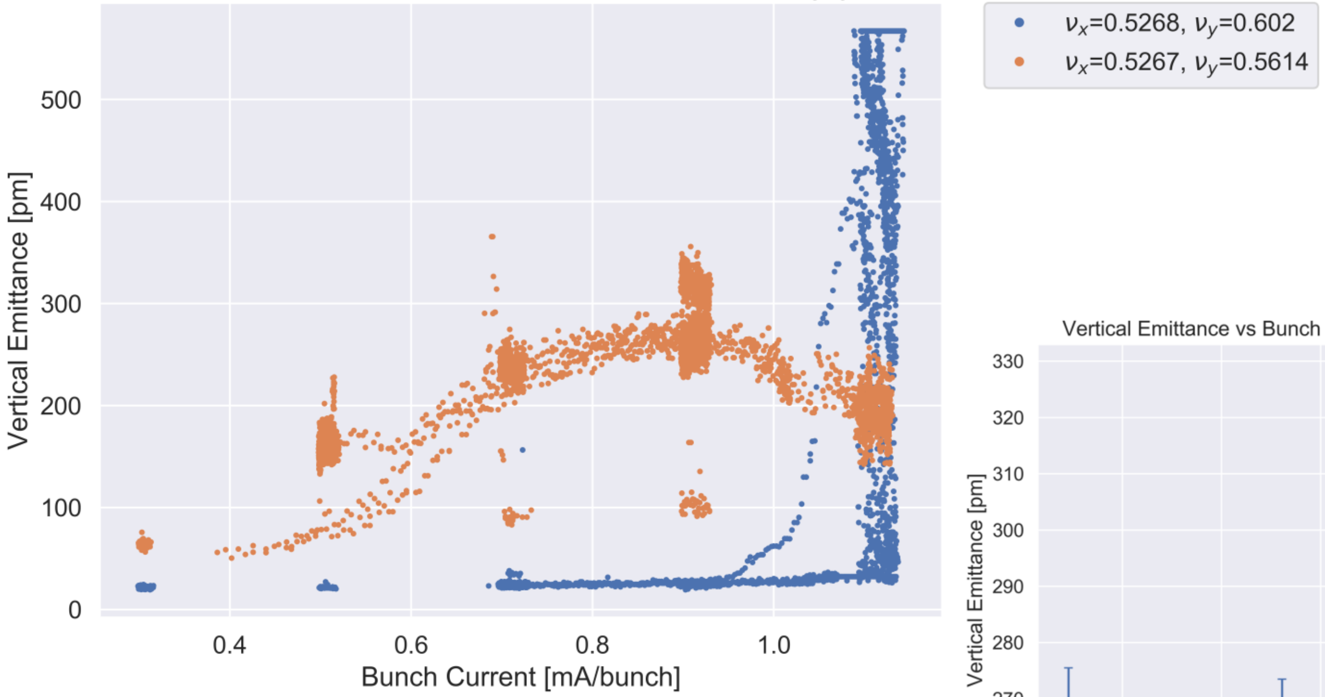
  - ➢ *A*~1 in D. Zhou's simulations.
  - ➢ *A*>2 In measurements using streak camera.

- We can explain that the measured resonance is caused by ν_y-ν_x-2ν_s assuming the bunch lengthening with *A*~1.44 m/A in the model lattice.

Emittance depending on ν_y and wake strength

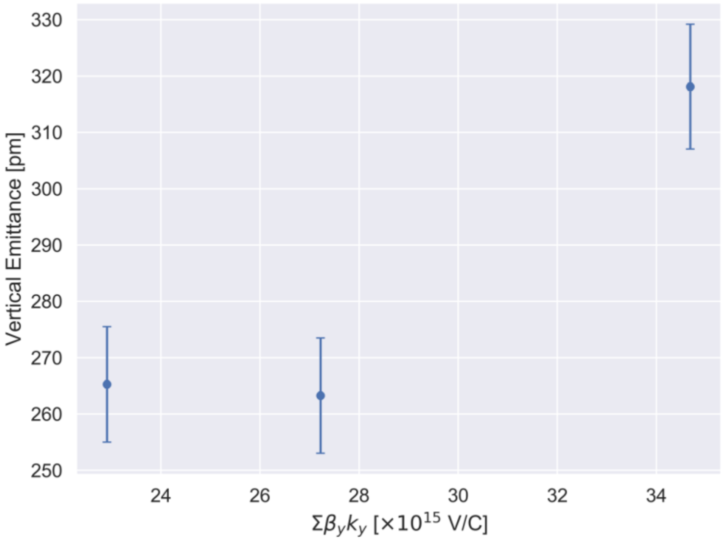
β_y^*=8mm

Vertical Emittance vs Bunch Current with different vertical tunes ($\Sigma\beta_y k_y$=3.47e+16 V/C)



- The vertical emittance around ν_y=0.5614 is large even if the bunch current is low.
- When ν_y>0.6, the vertical emittance increases instantaneously for bunch current of ~1.1 mA. This seems ordinary mode coupling.

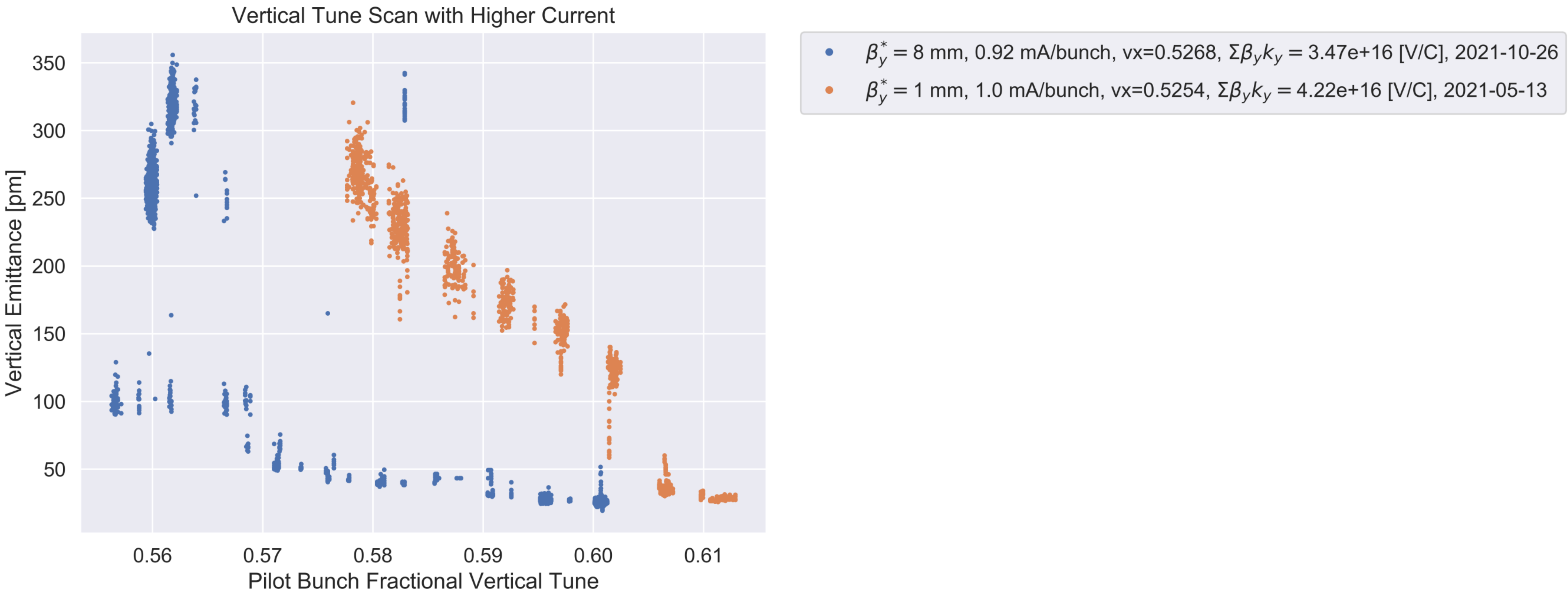
Vertical Emittance vs Bunch Current with D06V1 aperture setting



- The vertical emittance depends on the aperture of D06V1 collimator. The wake in D06V1 enhances the emittance increase.
- This indicates the wake contains x-y coupling component.

Operating point has to be chosen ν_y~0.6.

Tune scan (β_y*=1 mm vs 8 mm)



- In βy*=1 mm, the stop-band remarkably spreads.

Synchro-beta resonances

- Transfer matrix

$$M(\delta) = M_0 M_\xi(\delta)$$

$$M_\xi(\delta) = \prod_i^{n_\delta} M_i^{-1} K_i(\delta) M_i \qquad K_i(\delta)\text{: Skew Q, S …}$$

M_i: transfer matrix to i-th element

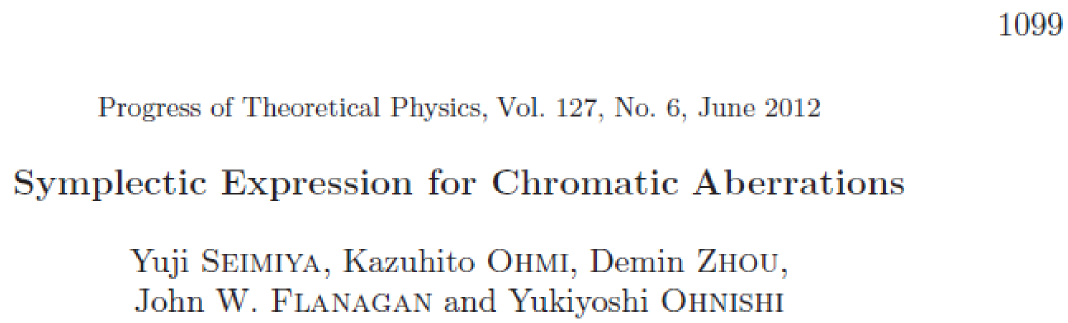
- Normal form, chromatic coupling

$$M(\delta) = R_\xi(\delta)\, M_0 R_\xi^{-1}(\delta)$$

  - $R_\xi(\delta)$ is observable.

$$R_\xi(\delta) = \begin{pmatrix} r_0(\delta) & 0 & & \\ 0 & r_0(\delta) & & \\ -r_1(\delta) & -r_2(\delta) & r_0 & 0 \\ -r_3(\delta) & -r_4(\delta) & 0 & r_0 \end{pmatrix}$$

- Relation of the two expression



1099

Progress of Theoretical Physics, Vol. 127, No. 6, June 2012

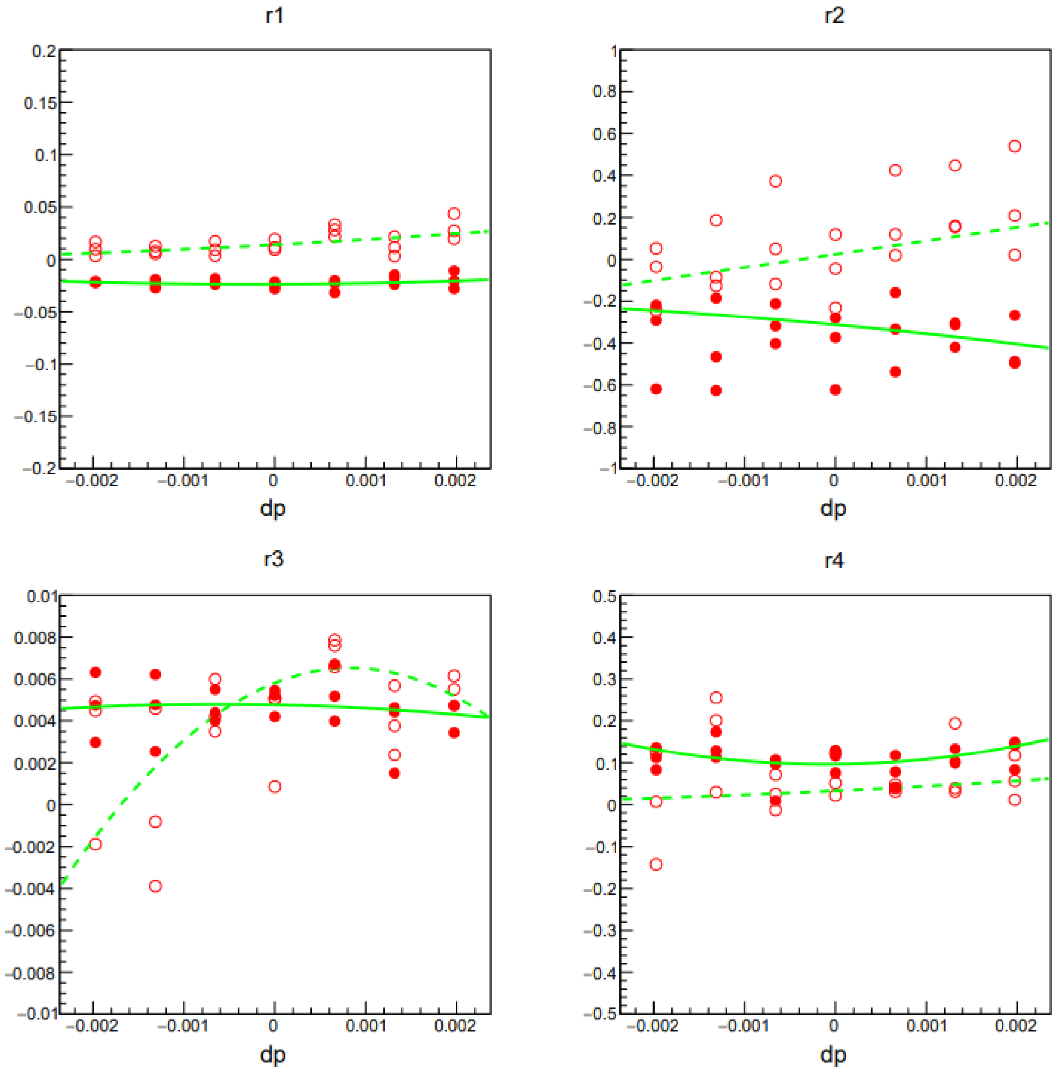
Symplectic Expression for Chromatic Aberrations

Yuji SEIMIYA, Kazuhito OHMI, Demin ZHOU,
John W. FLANAGAN and Yukiyoshi OHNISHI

$$M_\xi(\delta) = \exp(-{:}H{:})$$

Chromatic coupling near D6V1 (s=1869.97m) collimator

- Up and downstream of D6V1



β_y^*=1mm

-1.42809	239.171	-1533.81
6.76406	-980.588	7090.7
8.49025	347.503	-4032.6
-9.01979	-3522.6	11672.7

MQTAFOP1 s=1856.27m

	0−th	1st	2nd
r1	1.385e−02	4.622e+00	3.311e+02
r2	2.413e−02	6.325e+01	1.356e+02
r3	5.809e−03	1.702e+00	−1.021e+03
r4	3.335e−02	1.030e+01	7.765e+02

MQTAFOP2 s=1905.51

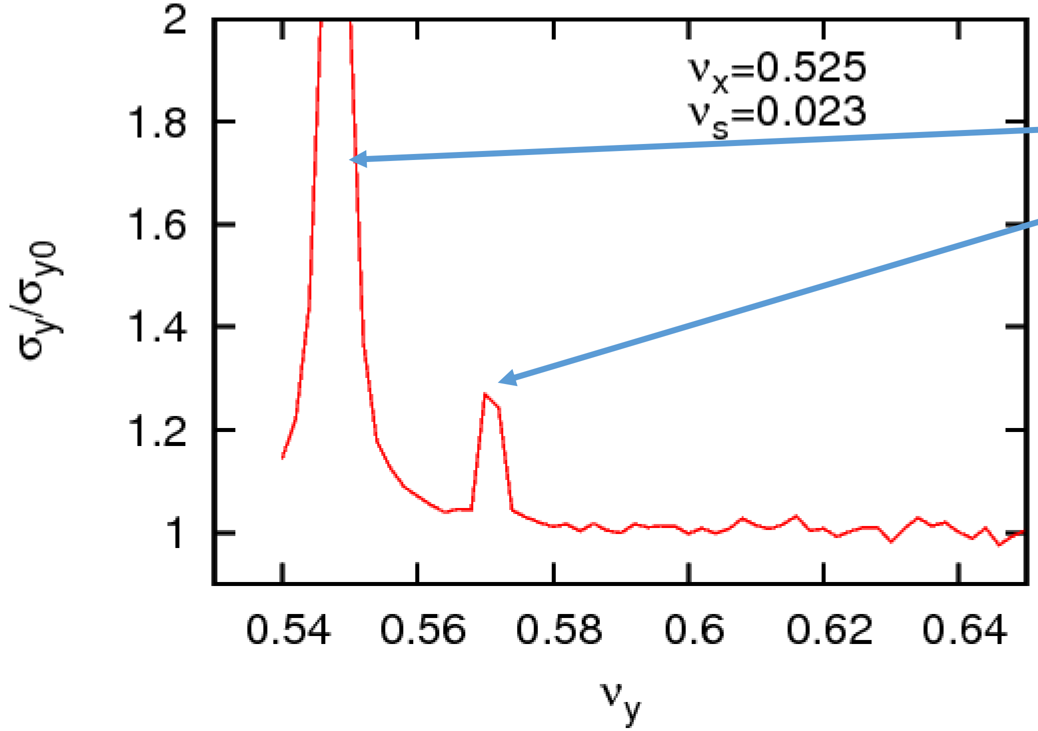
r1	−2.397e−02	3.010e−01	6.559e+02
r2	−3.127e−01	−4.007e+01	−3.035e+03
r3	4.764e−03	−9.001e−02	−7.185e+01
r4	9.628e−02	2.076e+00	1.006e+04

by G. Mitsuka

More accuracy is expected in the future.

Beam size for tune scan

- Tune scan is performed by $M_0 M_\xi(\delta)$. (4x4 formalism)
  - Measure chromatic coupling.
  - Calculate $M_\xi(\delta) = M_0^{-1} R_\xi(\delta)\ M_0 R_\xi^{-1}(\delta)$.
  - Tune scan is performed by changing M_0.
  - $R_\xi(\delta)$ is changed but $M_\xi(\delta)$ is kept in the tune scan (assumption).
  - Tracking simulation using $M_0 M_\xi(\delta)$ with keeping $M_\xi(\delta)$ in the tune scan.



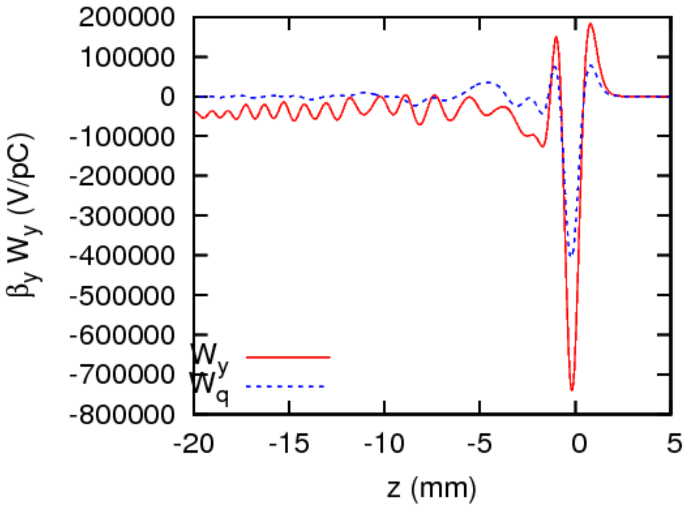
1^{st} and 2^{nd} sidebands are seen.

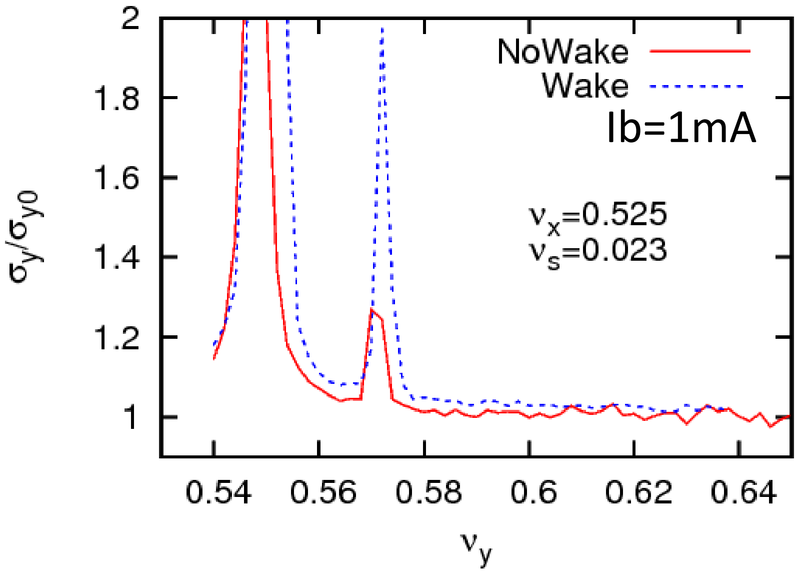
ε_{y0}=30pm

Simulation with Wake force and chromatic coupling

- Transverse wake is considered.

Preliminary



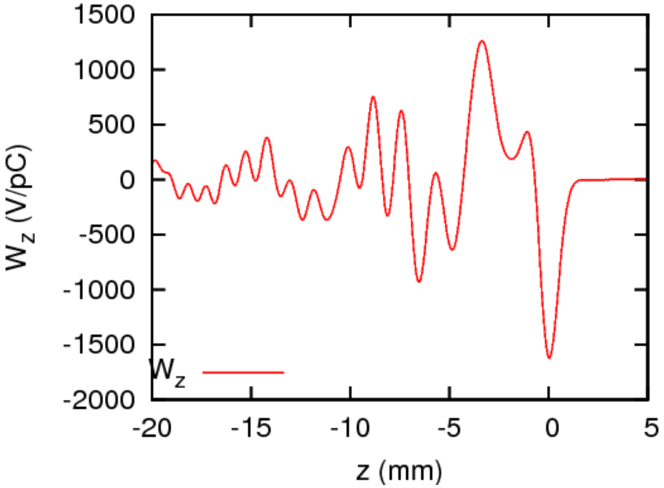


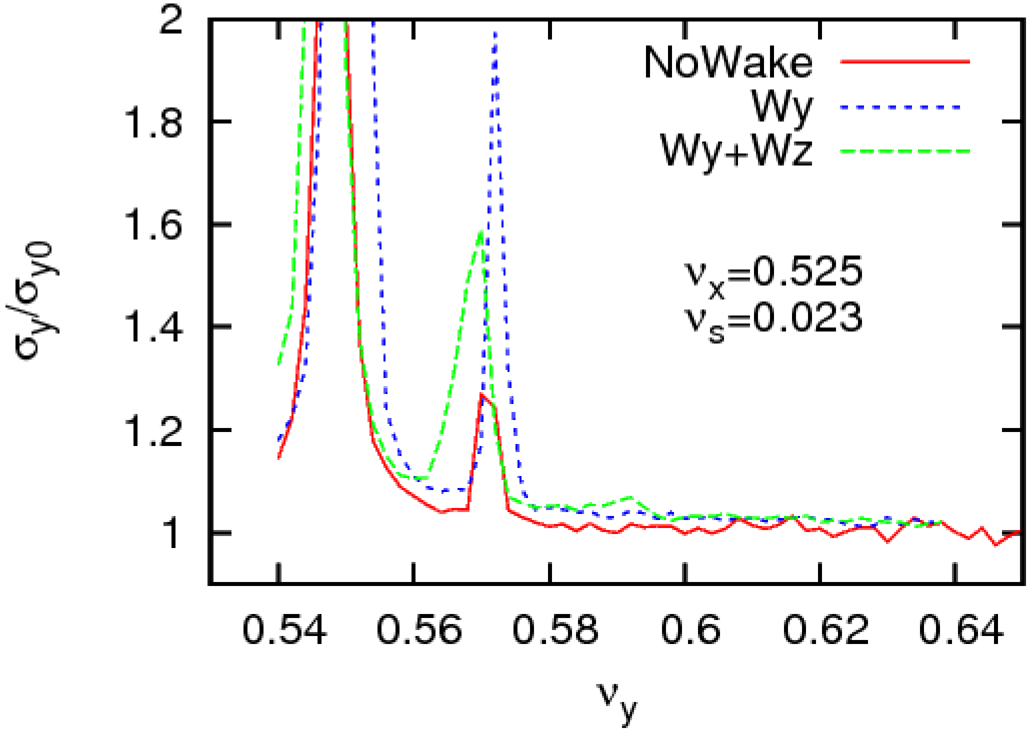
- Synchro-beta sidebands seems to be enhanced by the wake force.
- Beam is unstable at I_b=1.2mA in all tunes. This is threshold of the ordinary TMCI. Agreement with the measurement.

Simulation with Wake force(y+z) and chromatic coupling

- Longitudinal wake is added.

Preliminary





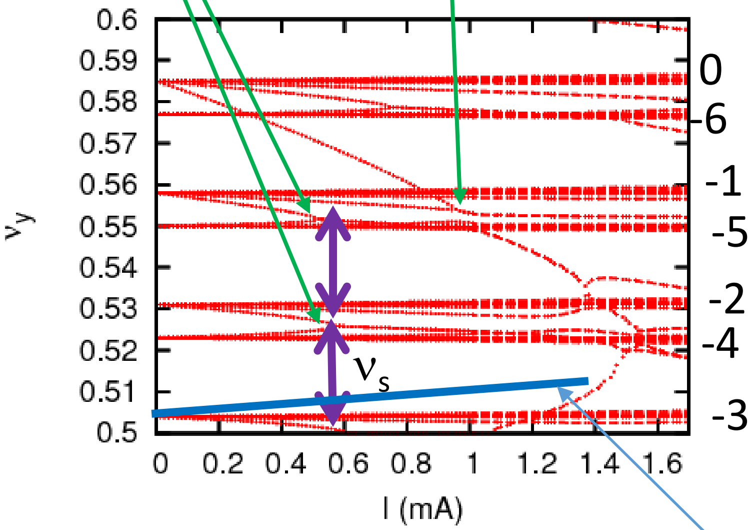
- Peaks of the synchro-beta resonances shift slightly lower.

Study for Mode coupling for localized wake

- In ordinary mode coupling, the betatron tune does not have meaning, but only tune different between sidebands, ns has meaning.
- In mode coupling due to a localized wake, the betatron tune has meaning. Sideband modes wrapped at 0.5.
- Threshold can be lower than that of ordinary TMCI.

Broad band resonator wake 50GHz, Q=1, no x-y coupling

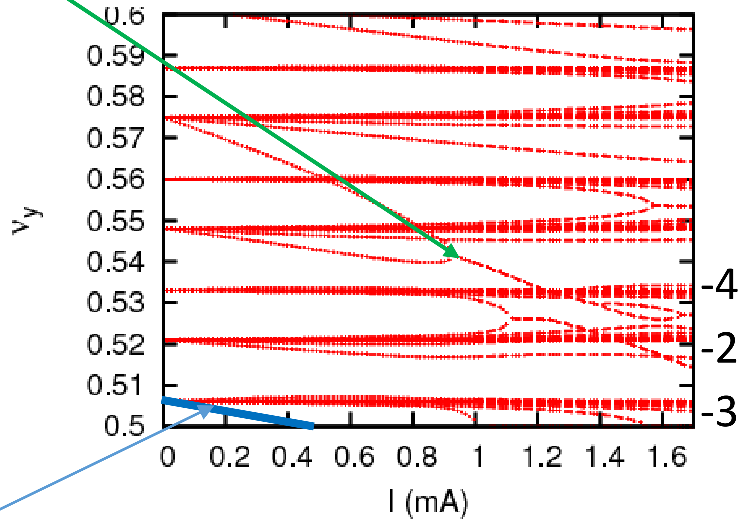
$\nu_y=0.585$



arbitrary

$2\nu_y-6\nu_s$ resonance

$\nu_y=0.575$



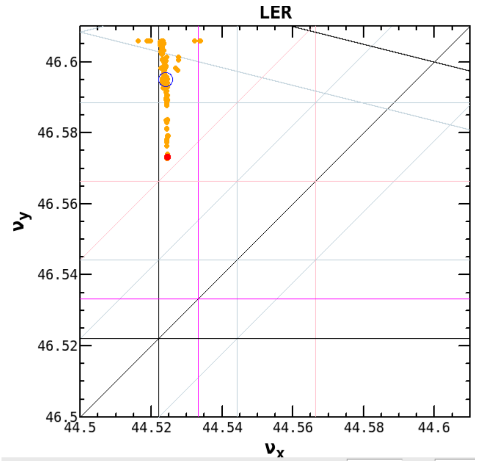
arbitrary

Experiments showed lower ν_y was worse.

This wake induces negative tune shift for -3 mode.
Positive tune shift is preferred to explain experimental results

Study for Mode coupling for x-y-z mode

- For ν_x-ν_y-2ν_s resonance, x-y-z mode coupling



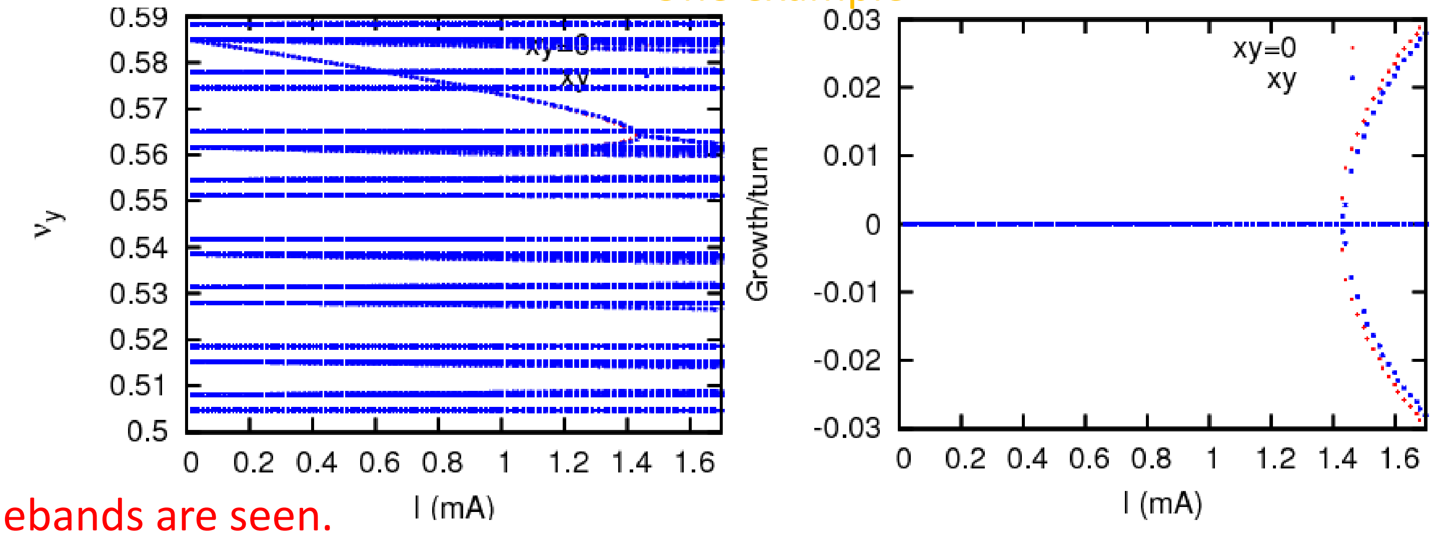
$$M_0 = e^{-2\pi i l \nu_s} R \begin{pmatrix} \cos\mu_x & \sin\mu_x & 0 & 0 \\ -\sin\mu_x & \cos\mu_x & 0 & 0 \\ 0 & 0 & \cos\mu_y & \sin\mu_y \\ 0 & 0 & -\sin\mu_y & \cos\mu_y \end{pmatrix} R^{-1}$$

$$M_W = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -W^{(x)}_{l,l'}(J,J')\psi(J')dJ' & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -W^{(y)}_{l,l'}(J,J')\psi(J')dJ' & 1 \end{pmatrix}$$

- Eigenvalue for M=M_0M_W

Only vertical wake “d2_s0.5_dy0.5_250”
Coupling measured by TbT data
R1=0.0230, R2=0.426, R3=-0.00165,
R4=0.05457 at D6V1 (interpolated).

One example



Both of ν_x and ν_y and their sidebands are seen.

Summary

- Vertical Beam size blowup has been observed in SuperKEKB-LER.
- The threshold is lower than that of the ordinary TMCI at $\nu_y < 0.6$. The blowup is related to a resonance $\nu_x - \nu_y + 2\nu_s$.
- The threshold at ν_y>0.6 is around Ib~1.2mA, while the design is Ib=1.4mA. This seems to be the ordinary TMCI.
- The blowup for $\nu_x - \nu_y + 2\nu_s$ is caused by nonlinear chromatic coupling as a incoherent single particle effect.
- Increasing the bunch intensity and/or transverse impedance (collimator aperture) enhanced the blowup. It also couples to the transverse impedance.
- Squeezing β_y* enhanced.
- Preliminary simulations were shown to explain the phenomena at $\nu_y < 0.6$.
- Accuracy of chromatic coupling measurement is expected to be improved.
- The phenomena can be explained by x-y coupling at collimator, or even only W_y.
- Measurement of the beam frequency spectrum is key to solve the TMCI(generalized) issues.

Thank you for your attention

Equation for dipole and quadrupole wake

- Transverse motion
- Longitudinal motion is assumed to be solved independently.

Quadrupole wake induced by the monopole component

$$H = H_0 + \frac{Nr_e}{\gamma L}\left[xF_x(z) + yF_y(z) - \frac{x^2-y^2}{2}F_Q(z)\right]$$

$$H_0 = \frac{1}{2}\left[p_x^2 + K_x(\delta, s)x^2 + p_y^2 + K_y(\delta, s)y^2\right]$$

$$F_{x,y}(z) = \int_{-\infty}^{\infty} W_{x,y}(z-z')\rho_{x,y}(z')dz$$

$$F_Q(z) = \int_{-\infty}^{\infty} W_Q(z-z')\rho(z')dz$$

$$\begin{aligned}\Delta p_x(z) &= -\frac{Nr_e}{\gamma}(F_x(z) - F_Q(z)x(z)) \\ \Delta p_y(z) &= -\frac{Nr_e}{\gamma}(F_y(z) + F_Q(z)y(z))\end{aligned}$$