Effect of Bunch Feedback system to the luminosity of e+e- collider

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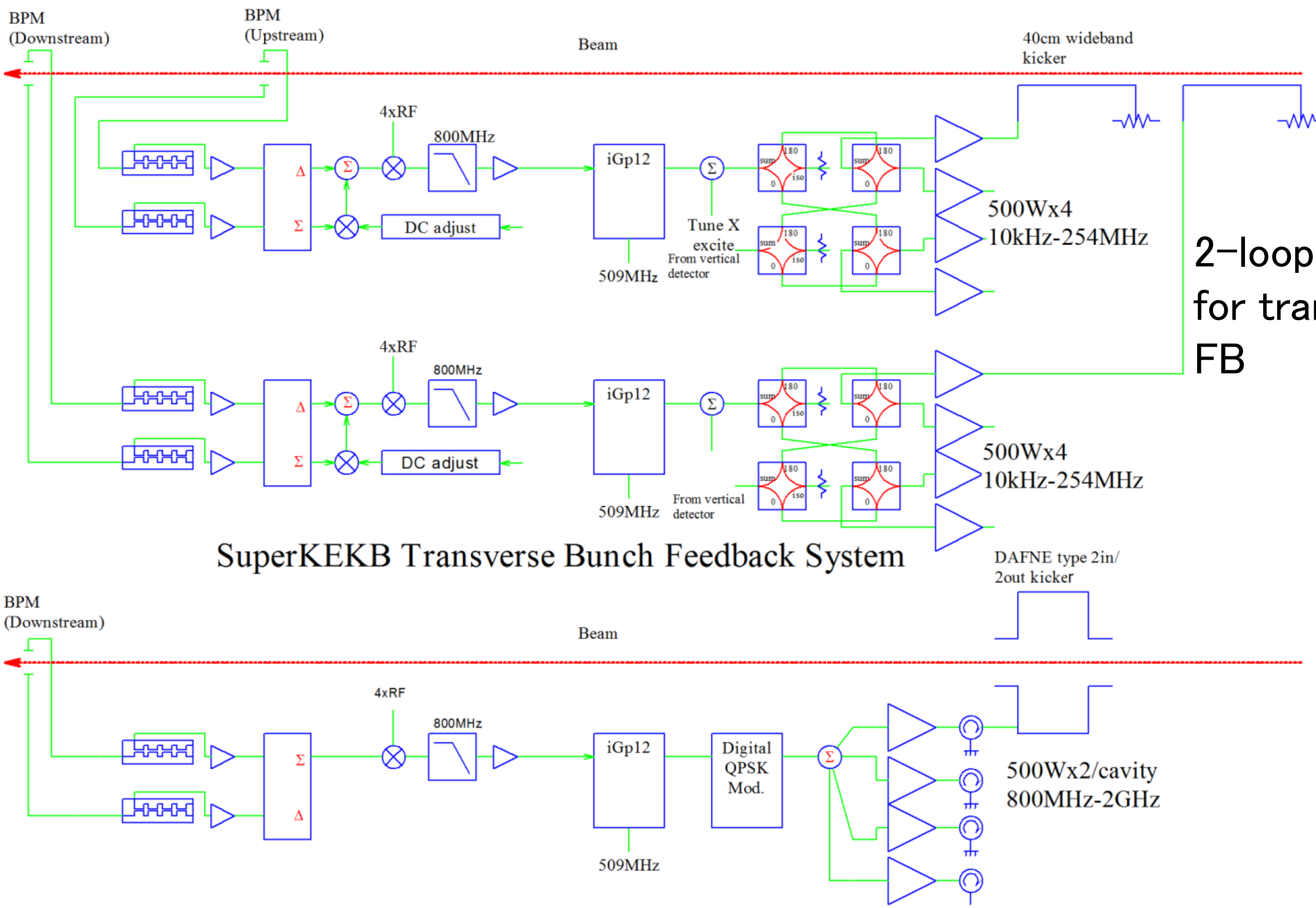
High beam current colliders

- **Complicated, many-mode coupled-bunch instabilities(CBI)**
  - Ion trapping, Fast Ion instability(HER electron)
  - Electron Cloud Instability (LER positron)
  - Trapped modes, HOMs of the vacuum components
  - Mode coupling instabilities from beam collimators
- **Suppress the CBI using BxB feedback**
  - Detect individual oscillations of all the bunches, calculate the feedback kick, then kick back individual bunch.
  - Transverse plane (Horizontal, Vertical)
  - Longitudinal plane

Bunch feedback systems (original)

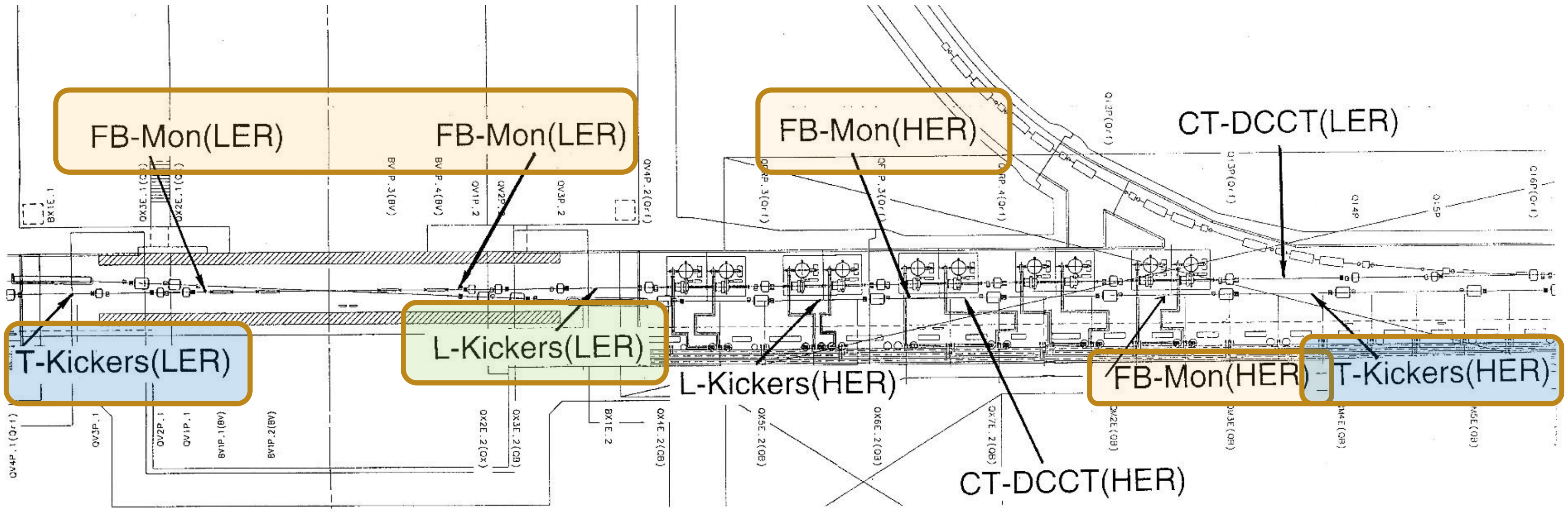


SuperKEKB Transverse Bunch Feedback System

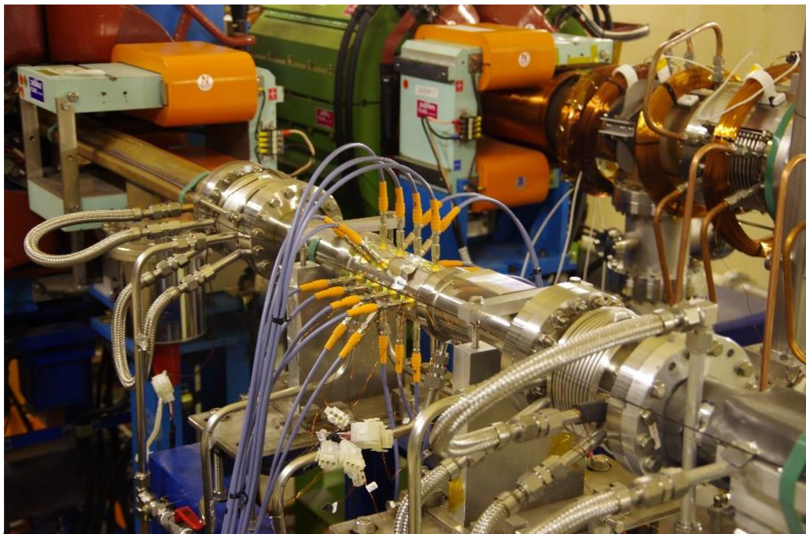
SuperKEKB Longitudinal Bunch Feedback System

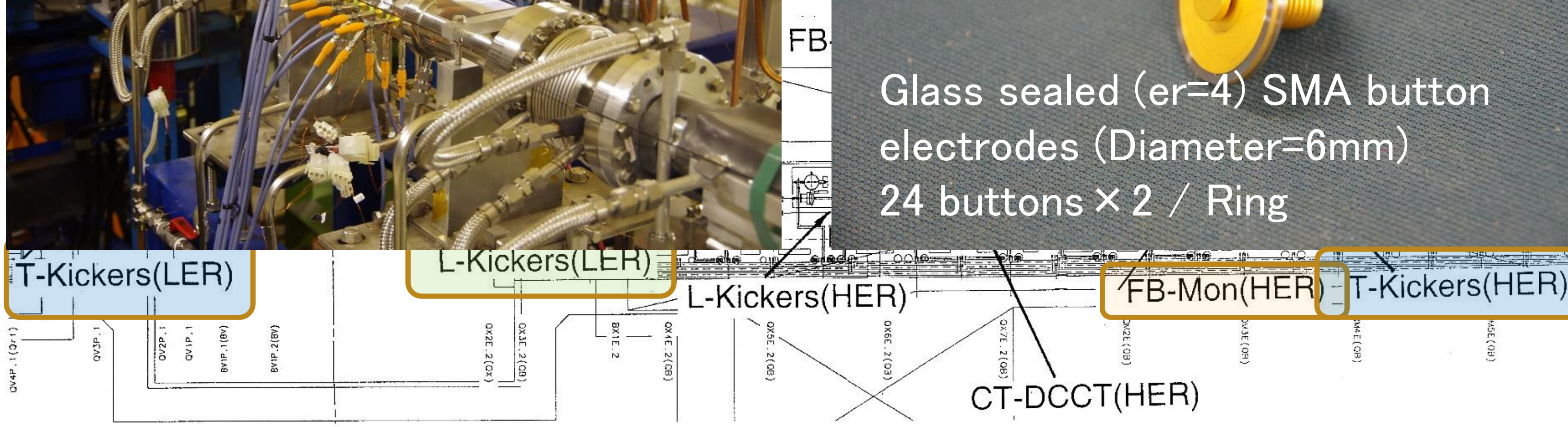
2-loops / plane for transverse FB

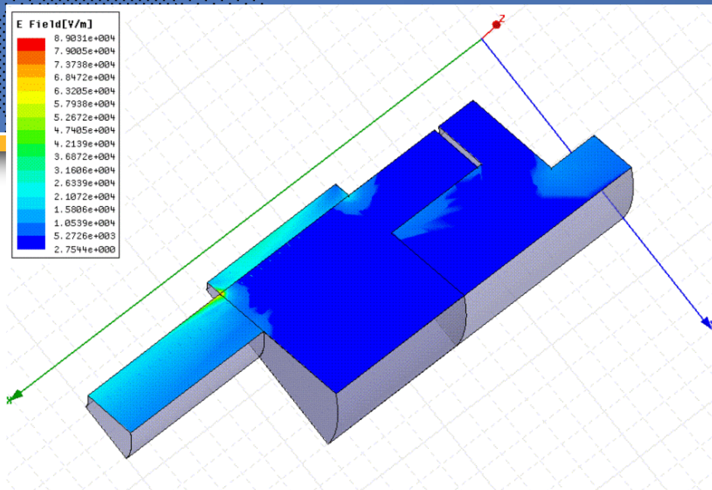
SuperKEKB Fuji straight section



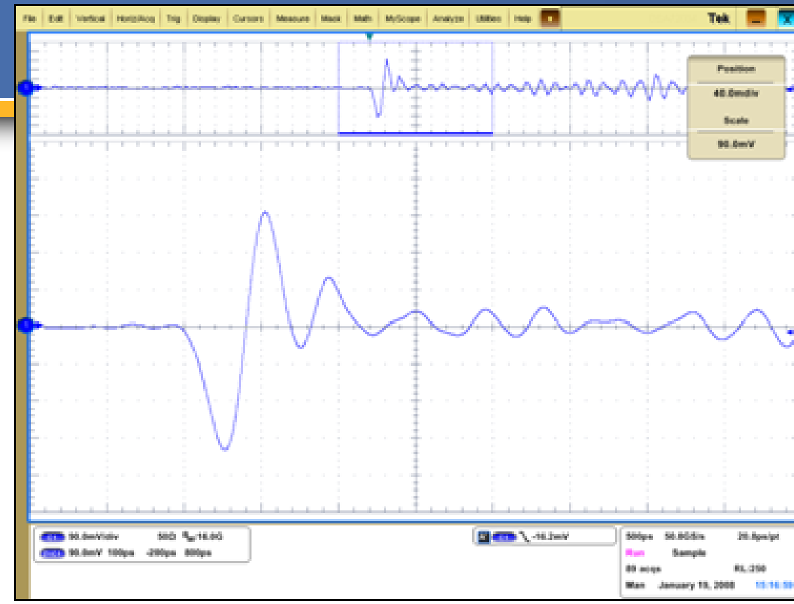
SuperKEKB Fuji straight section

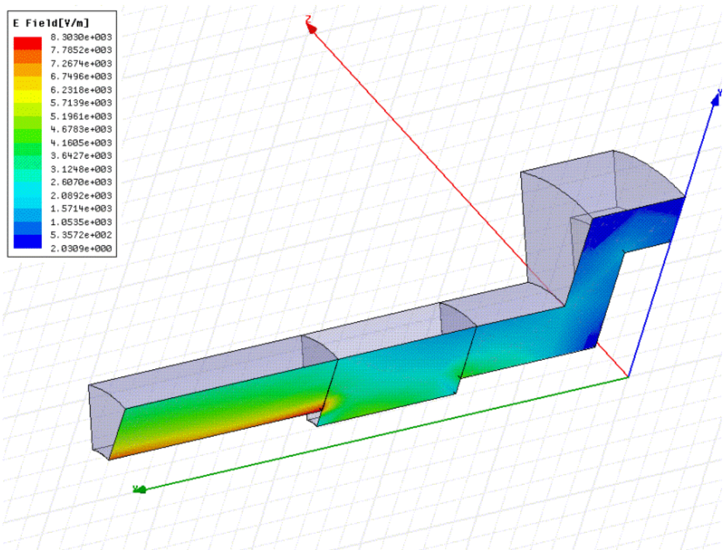




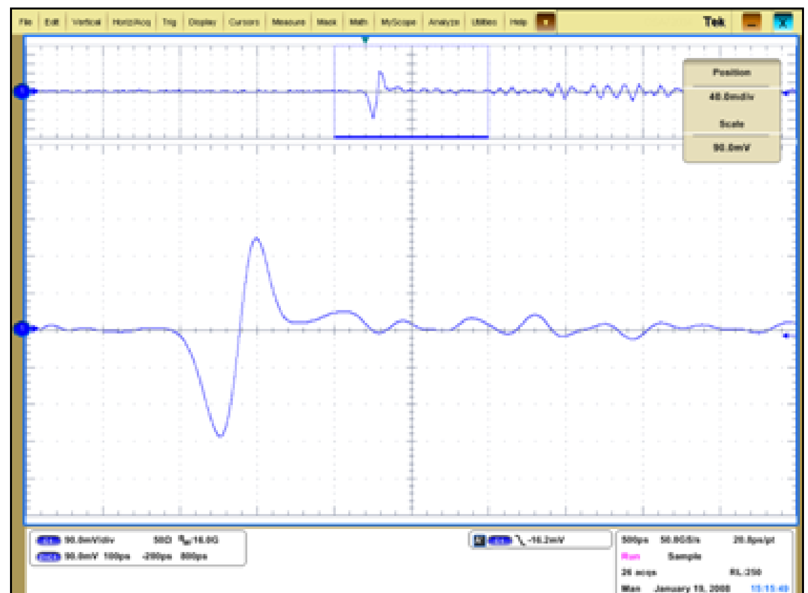


KEKB feedthrough for FB

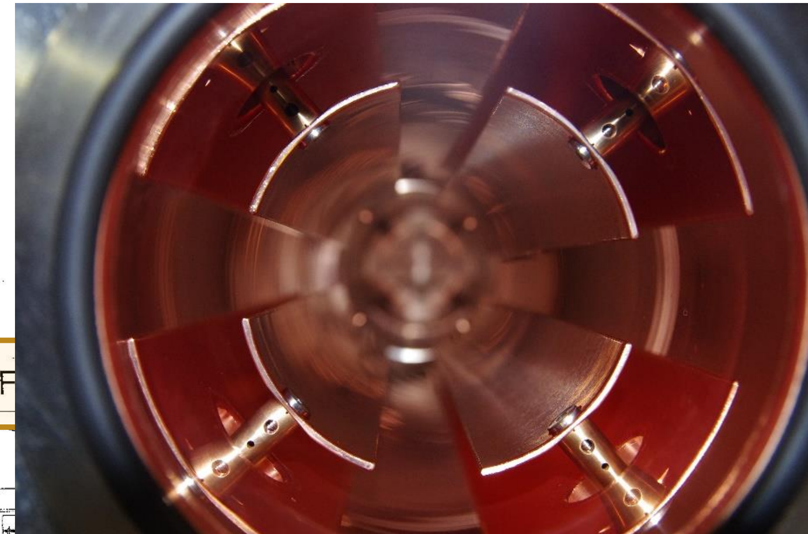




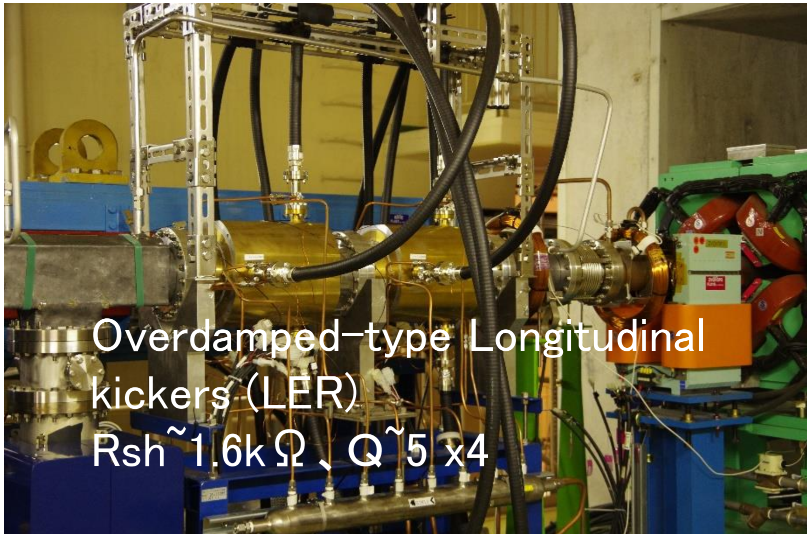
SuperKEKB FT for FB

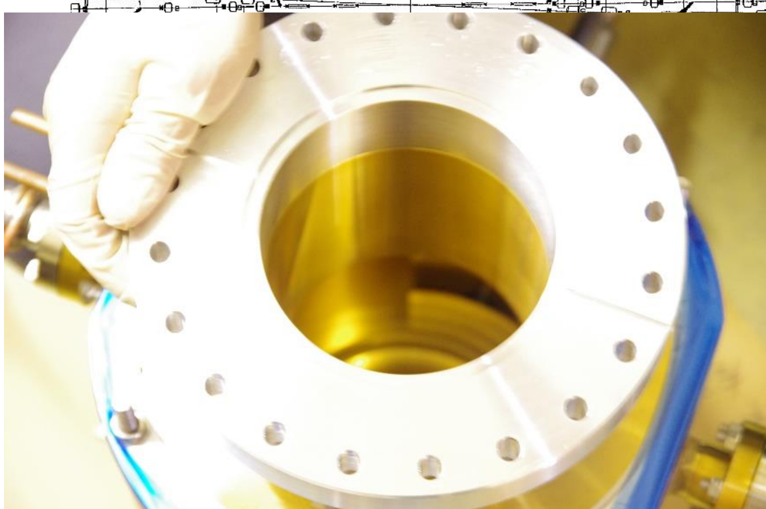


SuperKEKB Fuji straight section



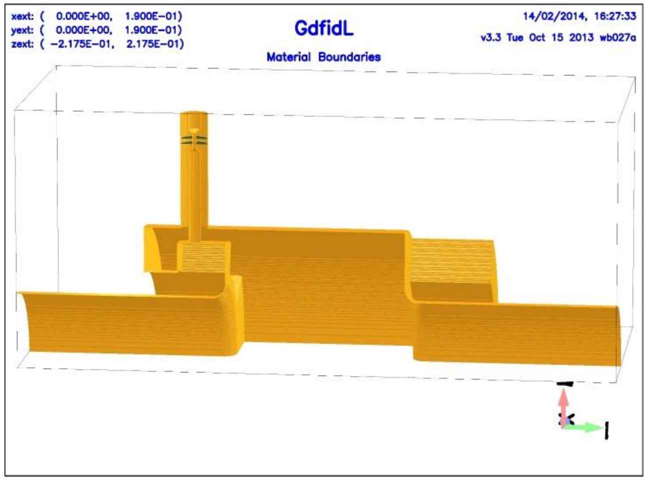
SuperKEKB Fuji straight section

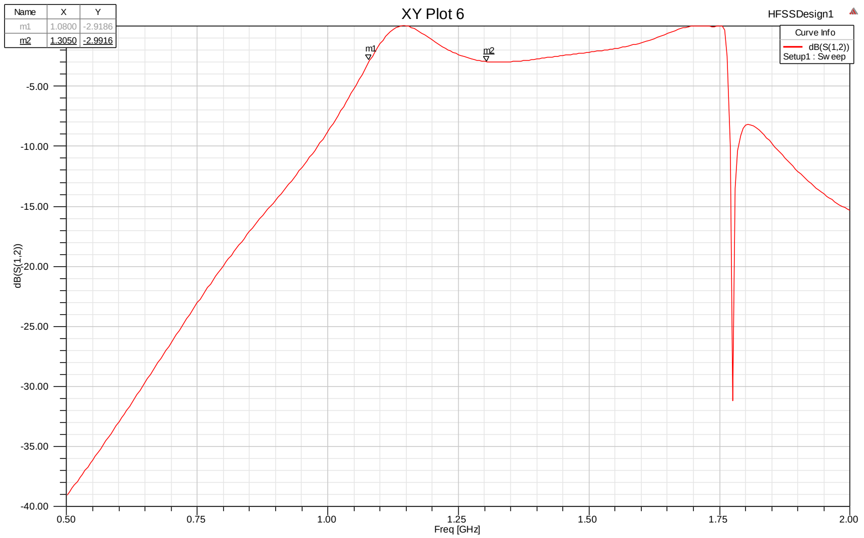




Longitudinal kicker

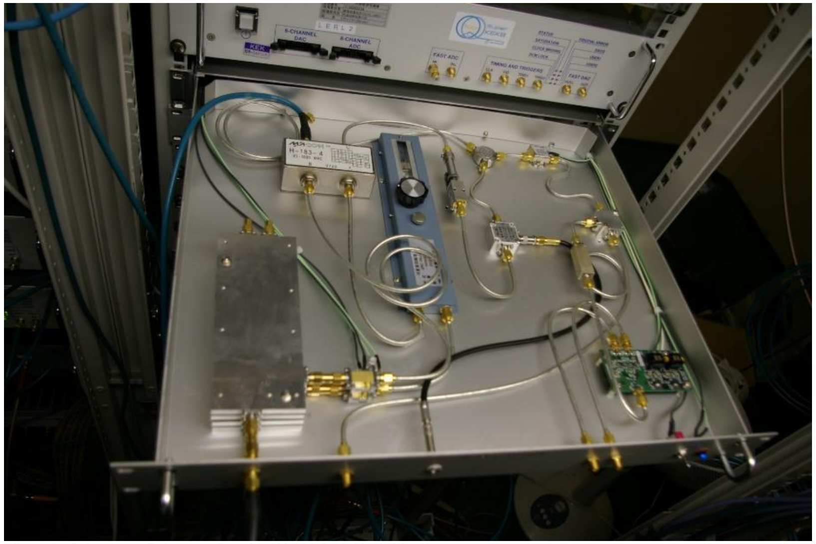
- 2-input, 2-output, DAFNE type kicker.
- center frequency =2.25 x fRF (1150 MHz)
- Bandwidth ~ 250MHz
- 8 wideband UHF amplifiers (R&K) are working (800M-1.8GHz, Po=500W).





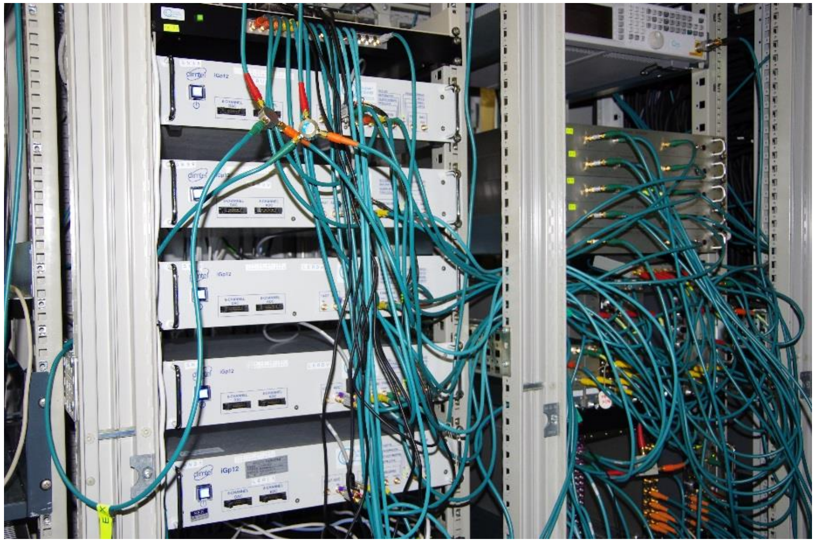
Q~ 5, Rsh ~ 1.6kΩ by HFSS calculation

Original FB detector



- Extract 2GHz(4xf_{RF}) components of a bunch using 3-tap comb filter
- Adjust the timing of two signals, subtract using H-184-3 Hybrid.
- Offset cancel circuit by adding sum signal to the differential signal
- Downconvert by 4xf_{RF}

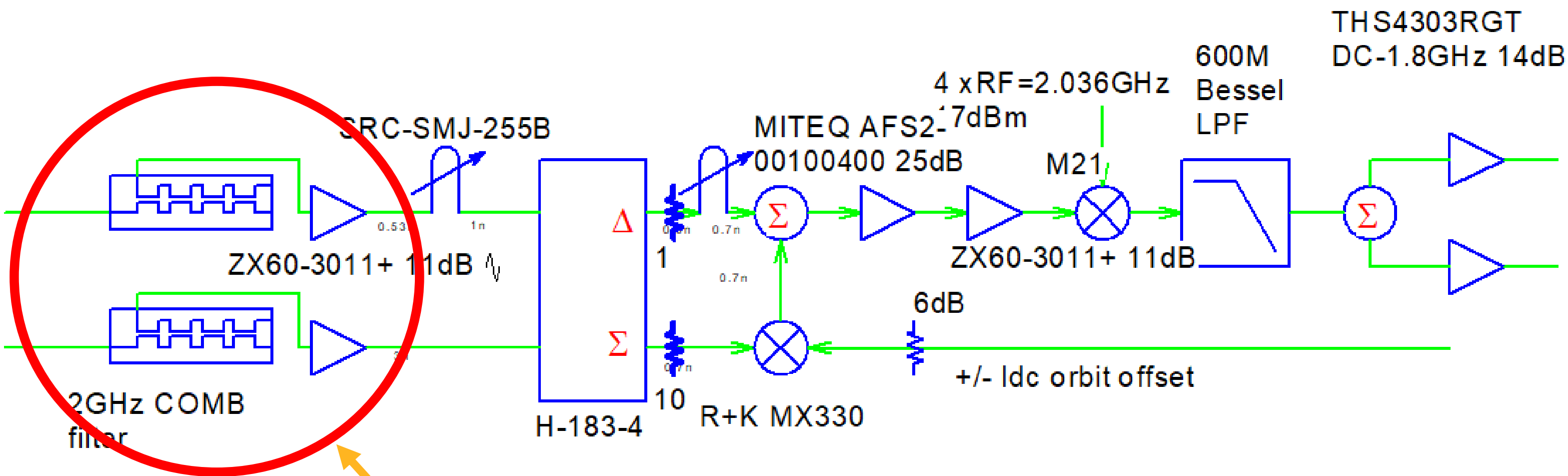
iGp12 Feedback processors (DimTel)



5 for LER (UH UV DH DV L)
5 for HER (UH UV DH DV L)
2 for positron DR (H V): VXS50T

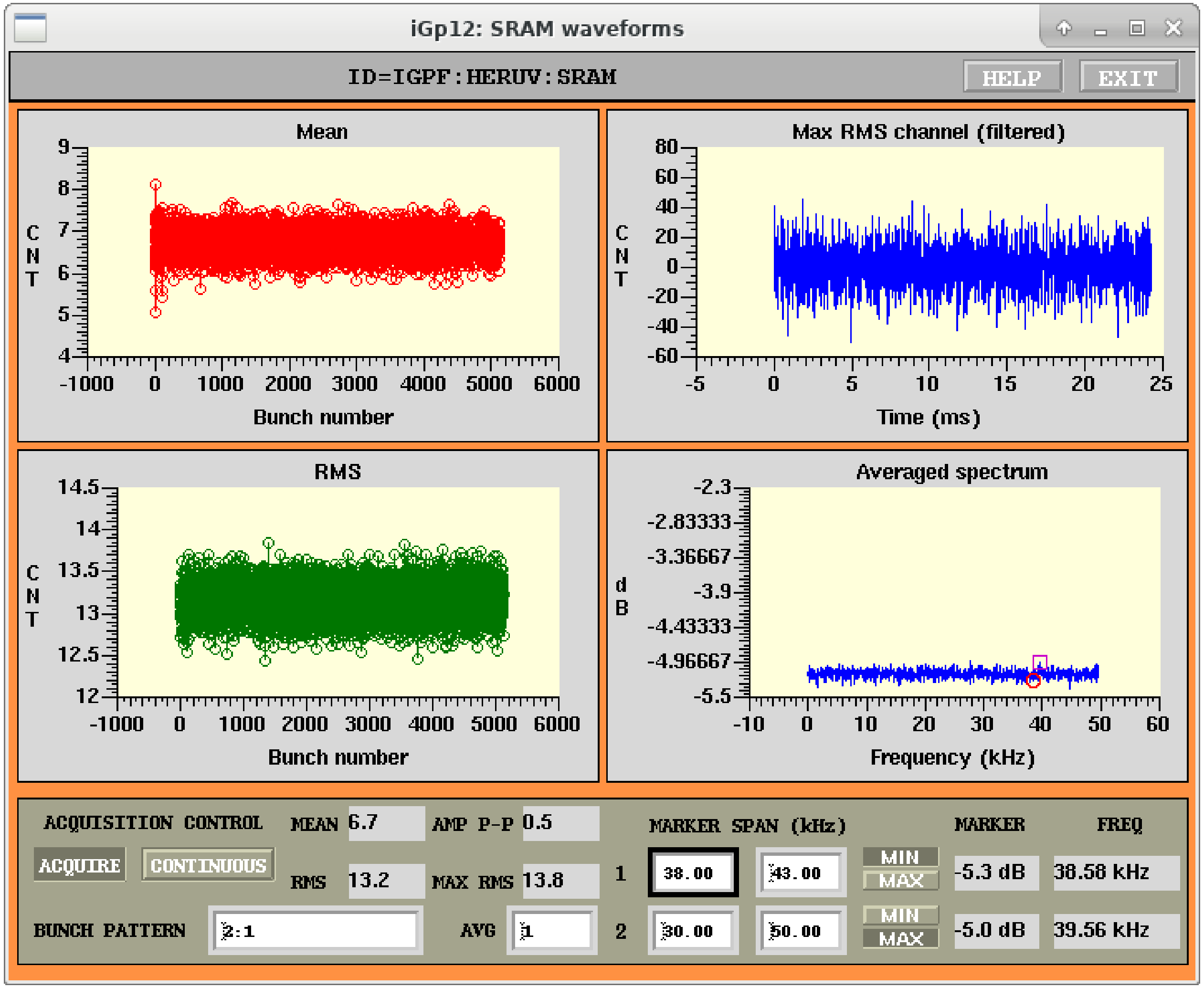
- 12bit ADC/DAC
- Virtex5 FPGA
  - VXS95T
- 17 tap FIR(h=5120)
- 12MB SRAM (transient-domain analysis)
- Single bunch beam transfer function measurements (using non-colliding bunch)

Original FB detector(transverse)



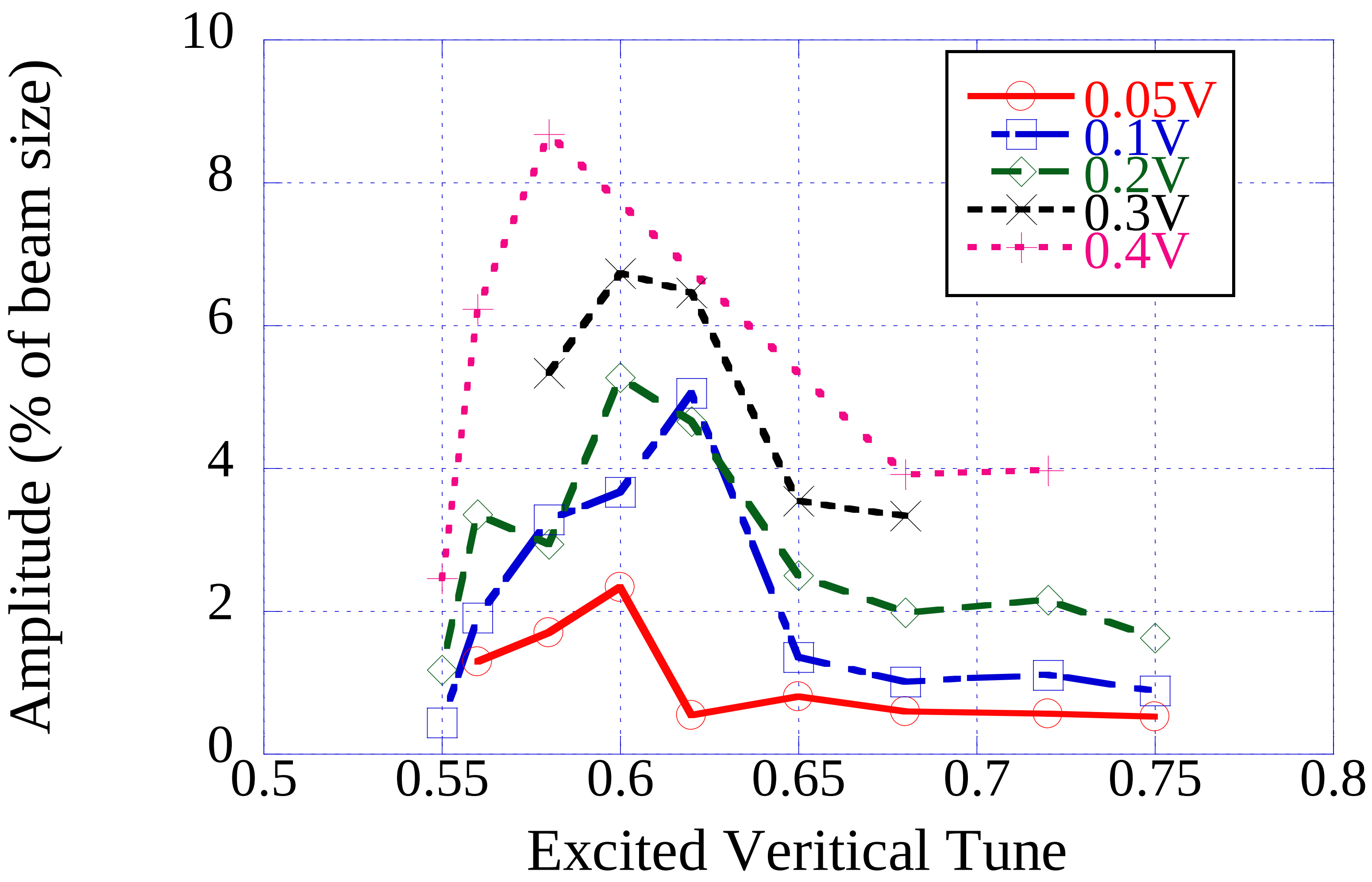
Large insertion loss (~22dB) and
need additional broadband amplifiers

Original broadband noise level

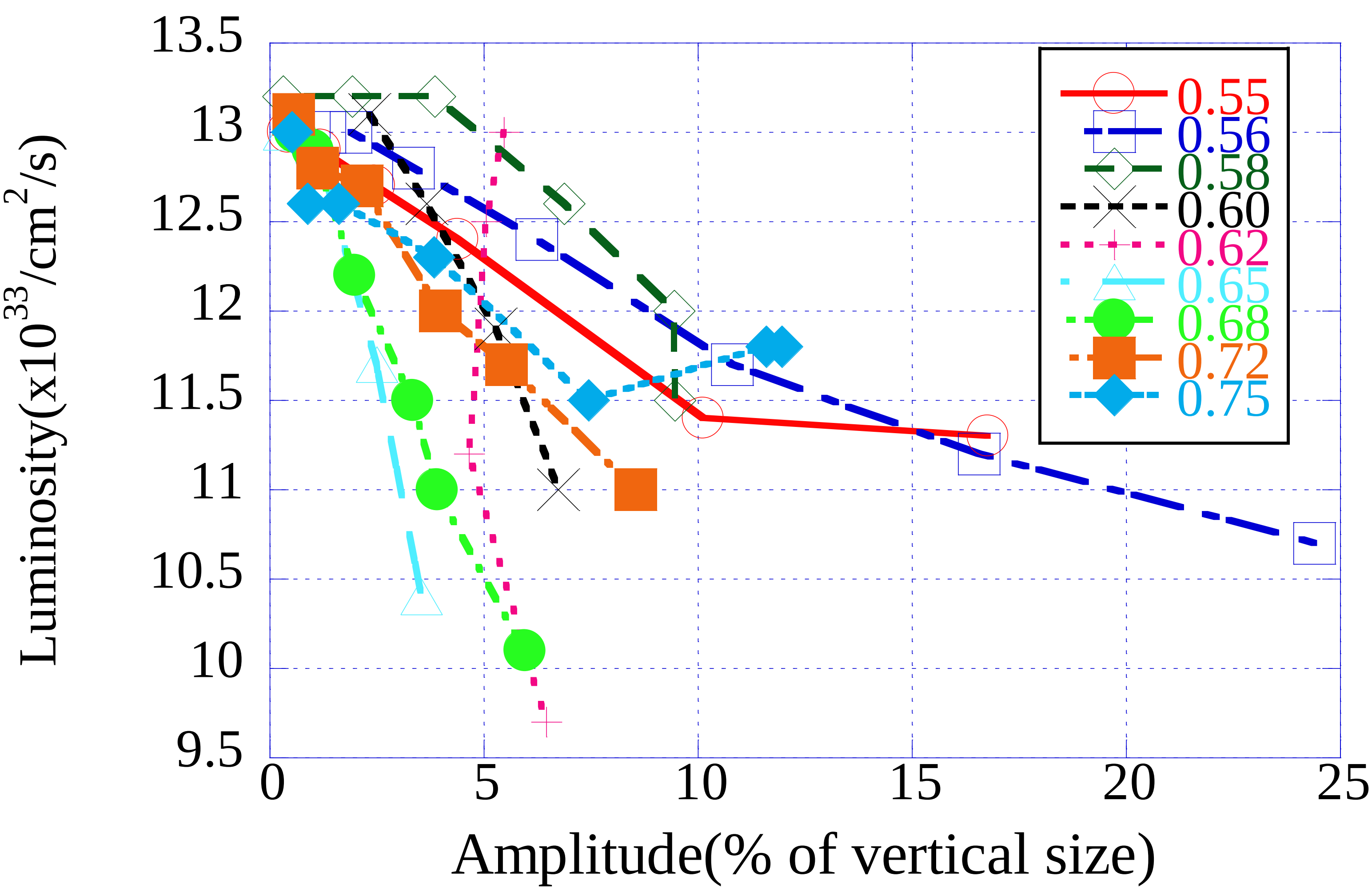


~13.2 counts in ADC of iGp12 (without beam)

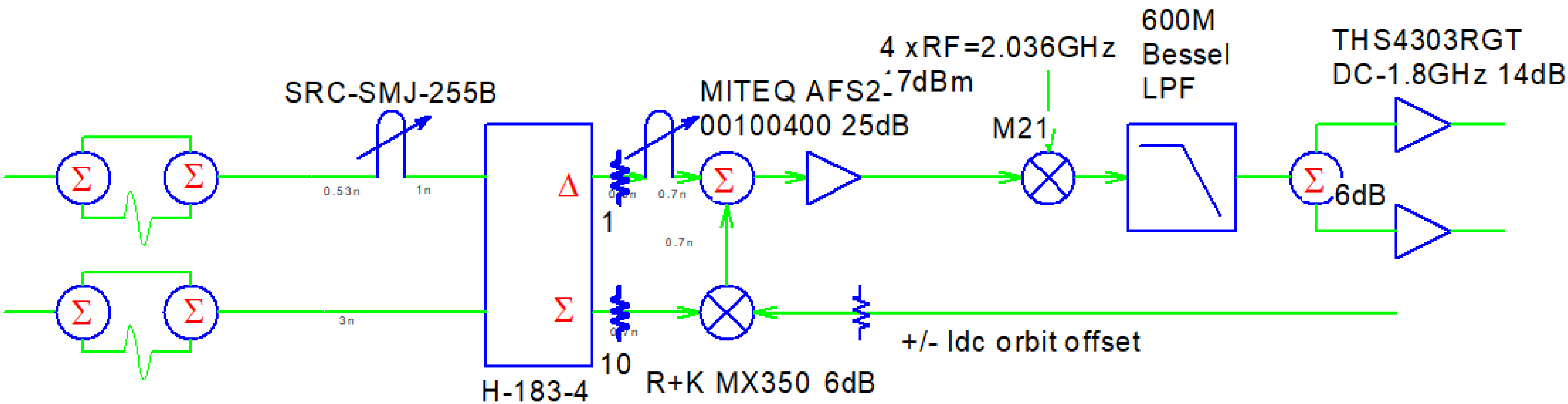
Frequency response of KEKB LER during collision



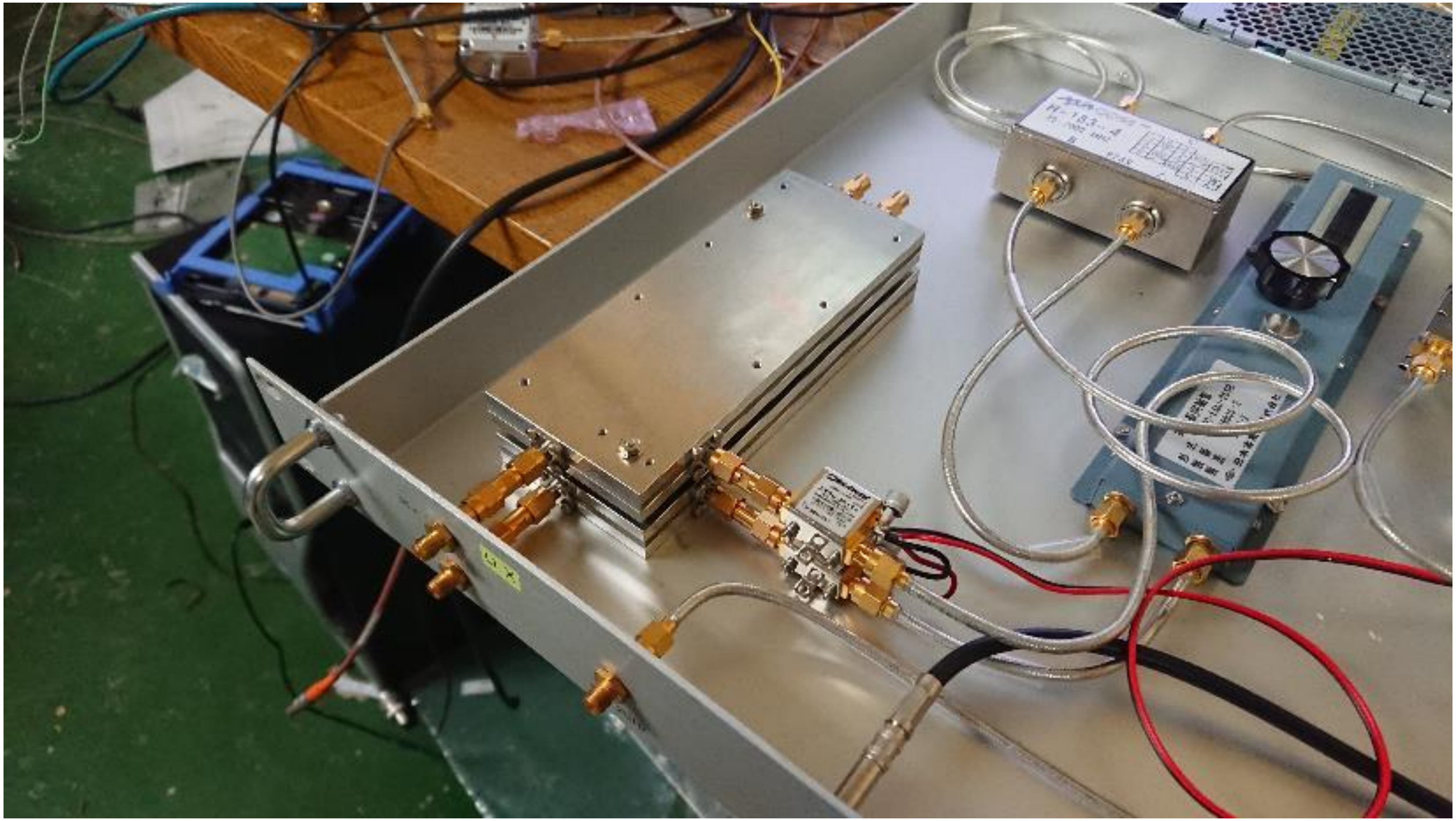
KEKB Luminosity drop with LER excitation



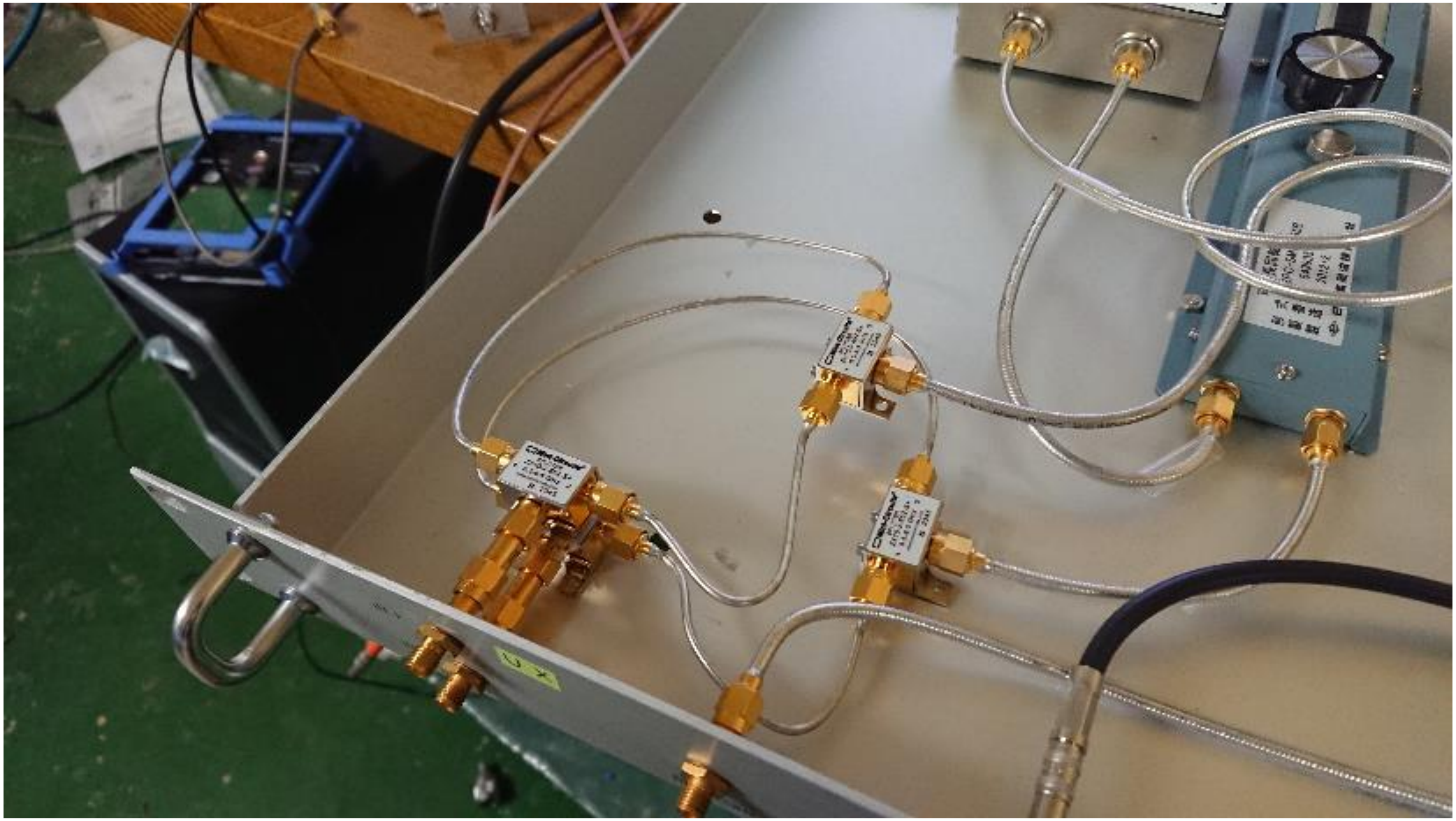
Updated FB Detector



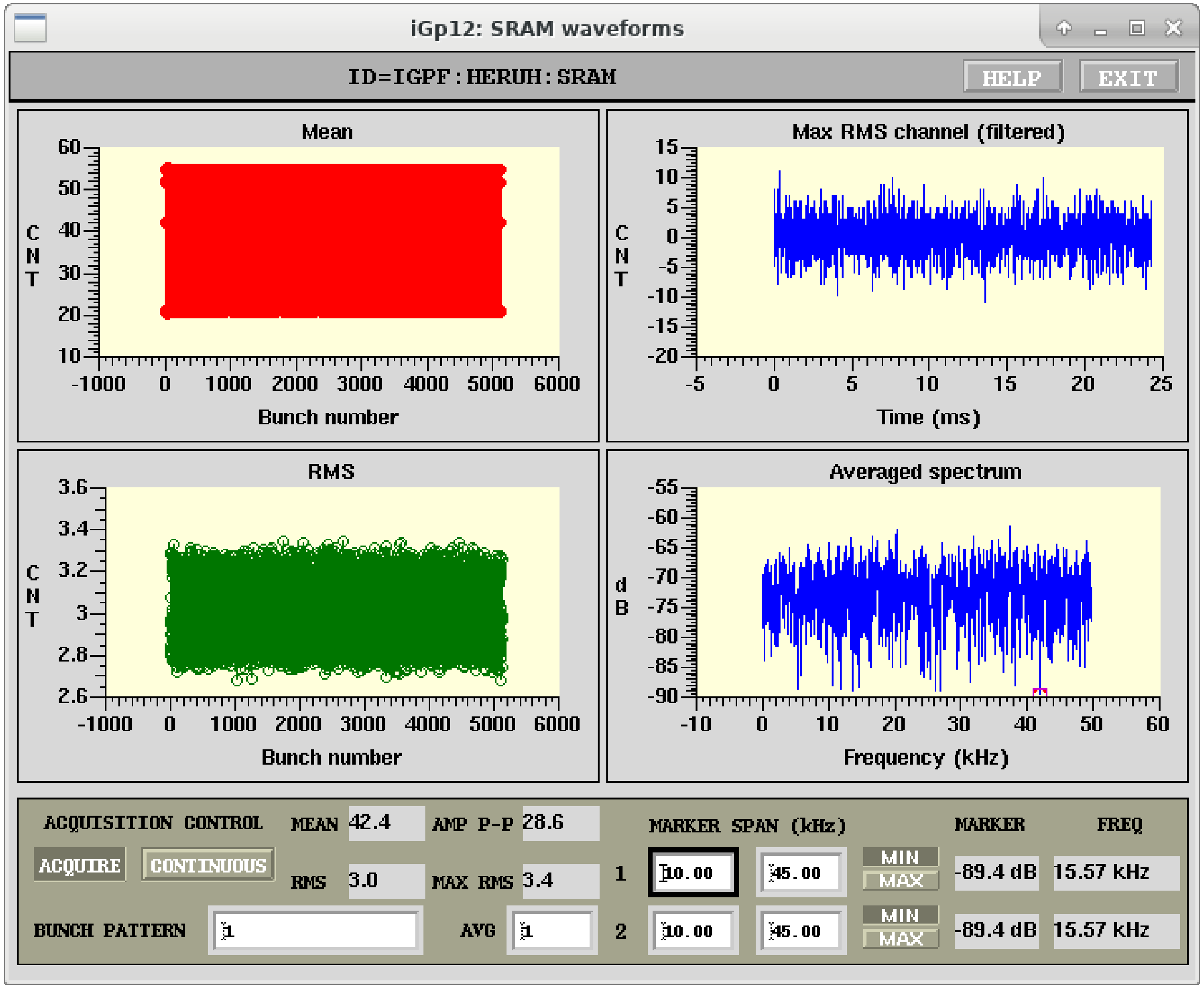
Original comb filter+amplifire



Cable type 2TAP BPF

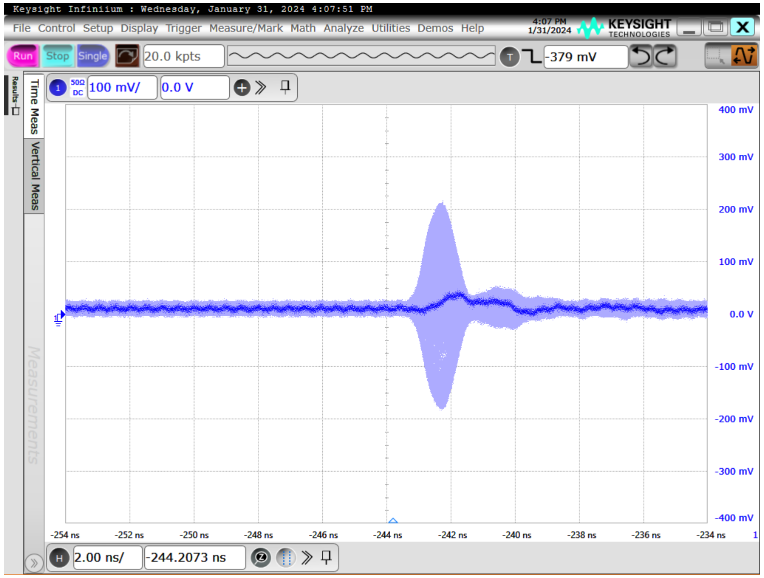


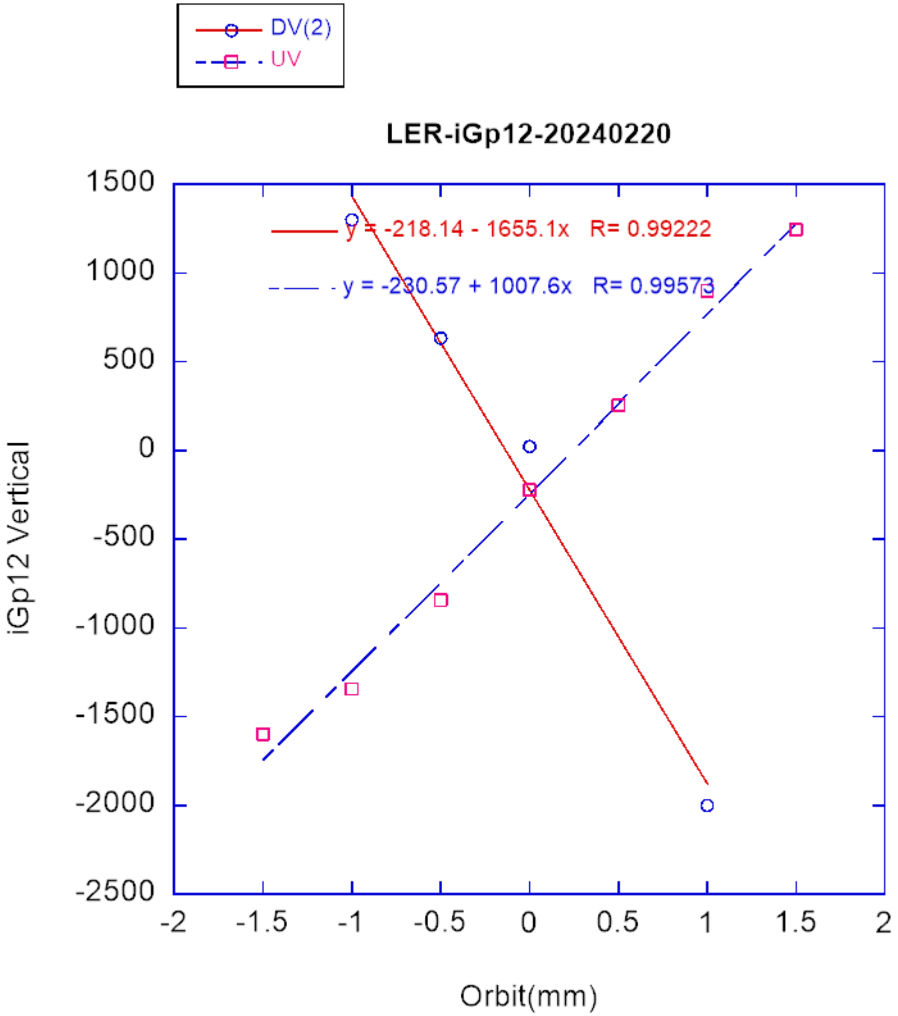
New noise level



Improved RMS 13->3

Detector output/sensitivities



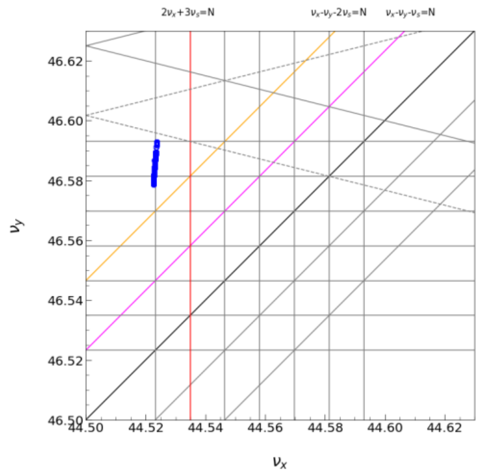


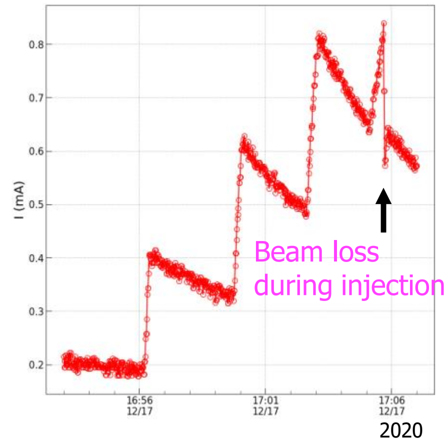
Dynamic range <+− 1.5mm /0.4mA @FB detector

Tuning transverse FB

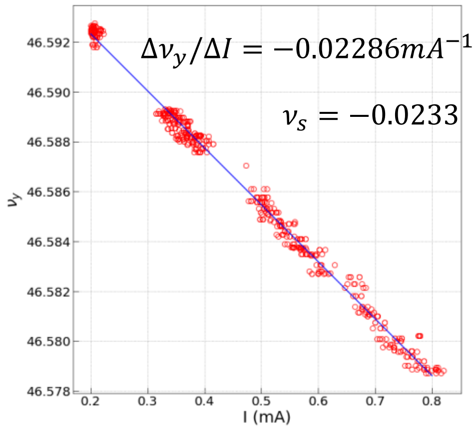
- **Tune FIR filters to be resistive, but not excite unwanted unstable modes such as coming mode coupling (not so visible this time), strange near half tune mode (imaginary tune split mode??)**
- **Tune the feedback gain to increase luminosity**
  - Exceed vertical feedback gain usually increases vertical beam size and reduce luminosity (LER)
  - Too low feedback gain also increase beam size and reduce luminosity (HER)

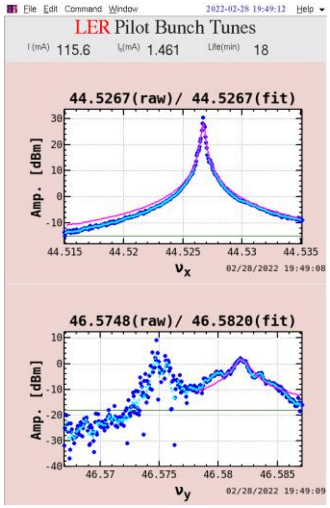
TMCI Observation at SuperKEKB



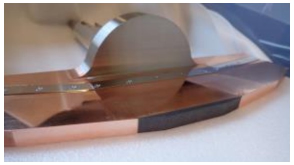


single bunch operation

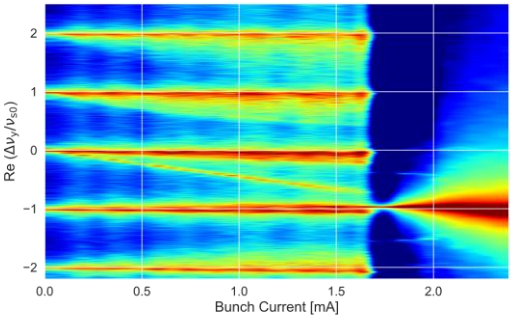




Tune measurement:
side band was observed
at high bunch current.



Simulation: PyHEADTAIL ($\Delta\nu_y/\Delta I \sim \nu_s/2$)



T. Ishibashi

We observed TMCI at SuperKEKB when we used a carbon head for one of the vertical collimators. The tune shift was similar to the synchrotron tune and the threshold was 0.85 mA/bunch. (2020)

We control the vertical collimator aperture to keep the tune shift less than half of ν_s.
The TMCT threshold becomes 1.7 mA/bunch in the LER for the normal operation.

* We replaced the carbon head with tantalum after this experiment.

Single Bunch Tune Shift and Impedance

Tune shift is equivalent to impedance.

Larger circumference (larger T_0) makes larger tune shift.

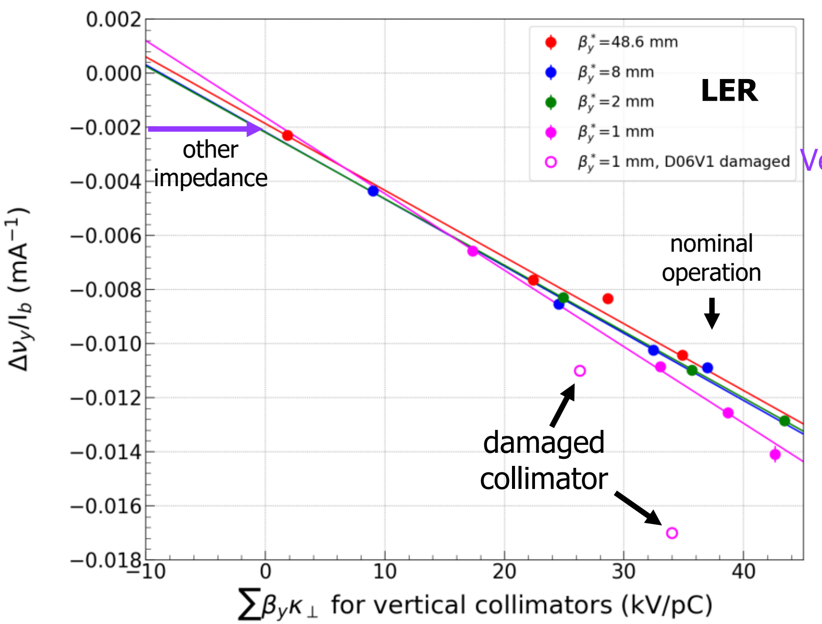
$$\frac{\Delta\nu_y}{I_b} = -\frac{T_0}{4\pi(E/e)}\sum_i \beta_{yi}\kappa_i(d)$$

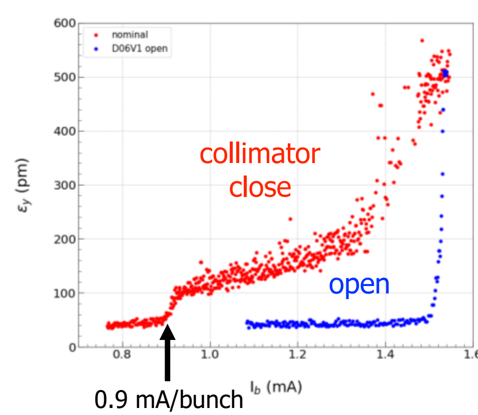
$$\rightarrow \frac{T_0}{4\pi(E/e)} = 0.2(ps/kV)$$ for SuperKEKB

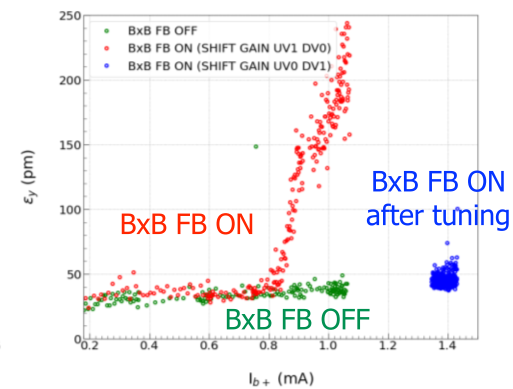
Kick factors of vertical collimators are calculated by GdfidL (and ECHO3D).

The vertical collimators contribute approximately 70 % of the total impedance.

Vetical beam size blowup was observed at much smaller than the TMCI threshold.
"-1 mode instability" ← impedance and BxB FB tuning

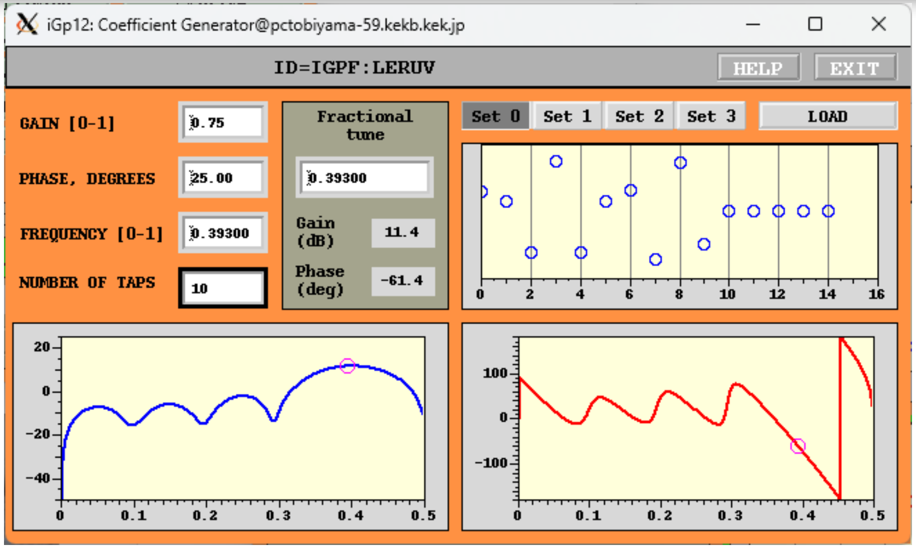






$\sum\beta_y\kappa = 33.3(kV/pC)$

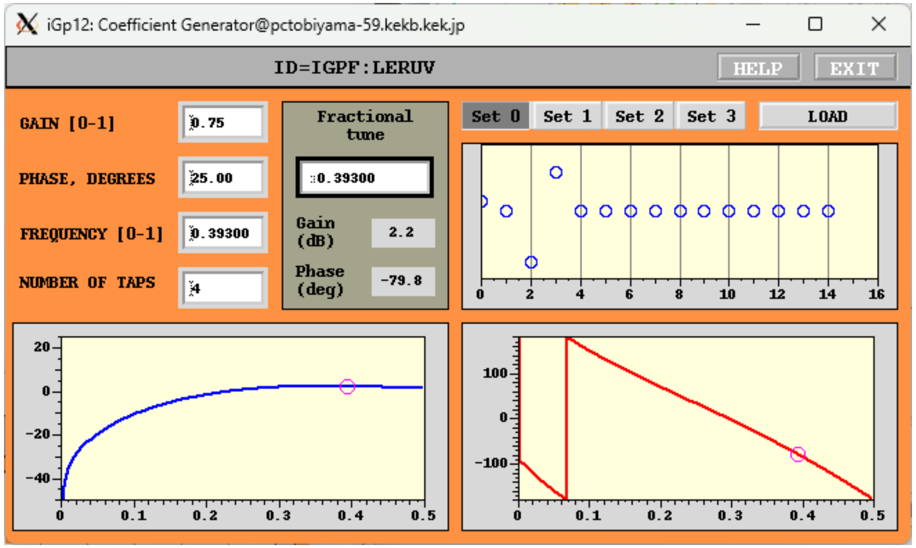
Length of FIR filter

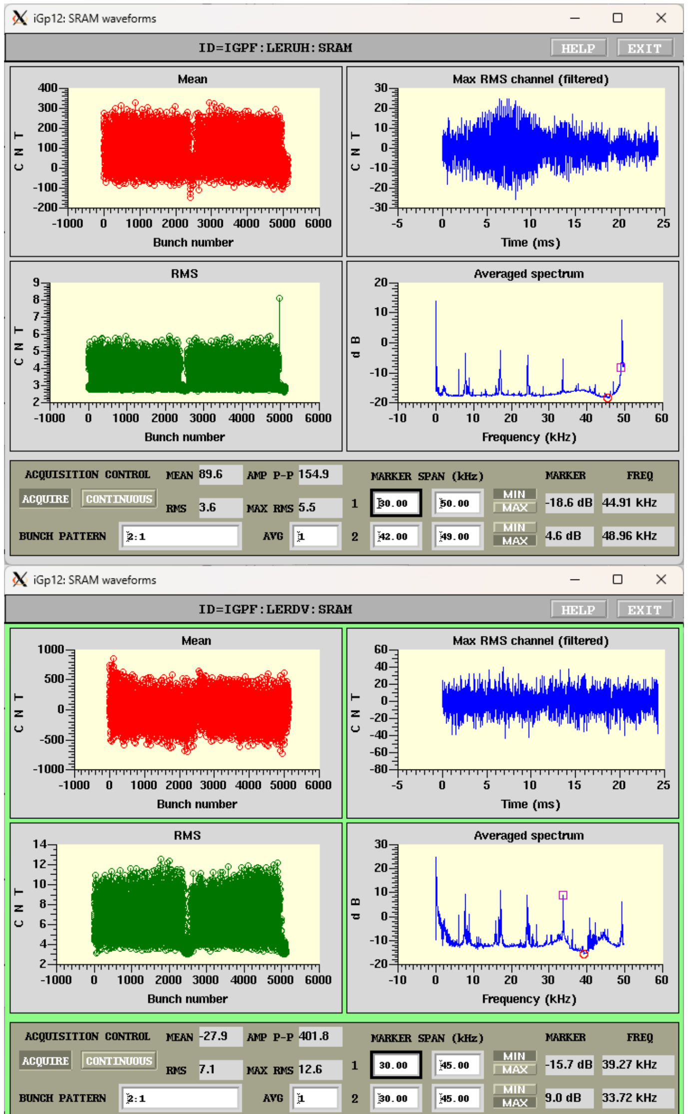


10 Tap FIR filter
Digital gain 11.4dB
FB phase diff@−1kHz : 18.7 deg

This could excite sideband coming from mode −1 related instability.

4 Tap FIR filter
Digital gain 2.2dB
FB phase diff@−1kHz : 8.7 deg





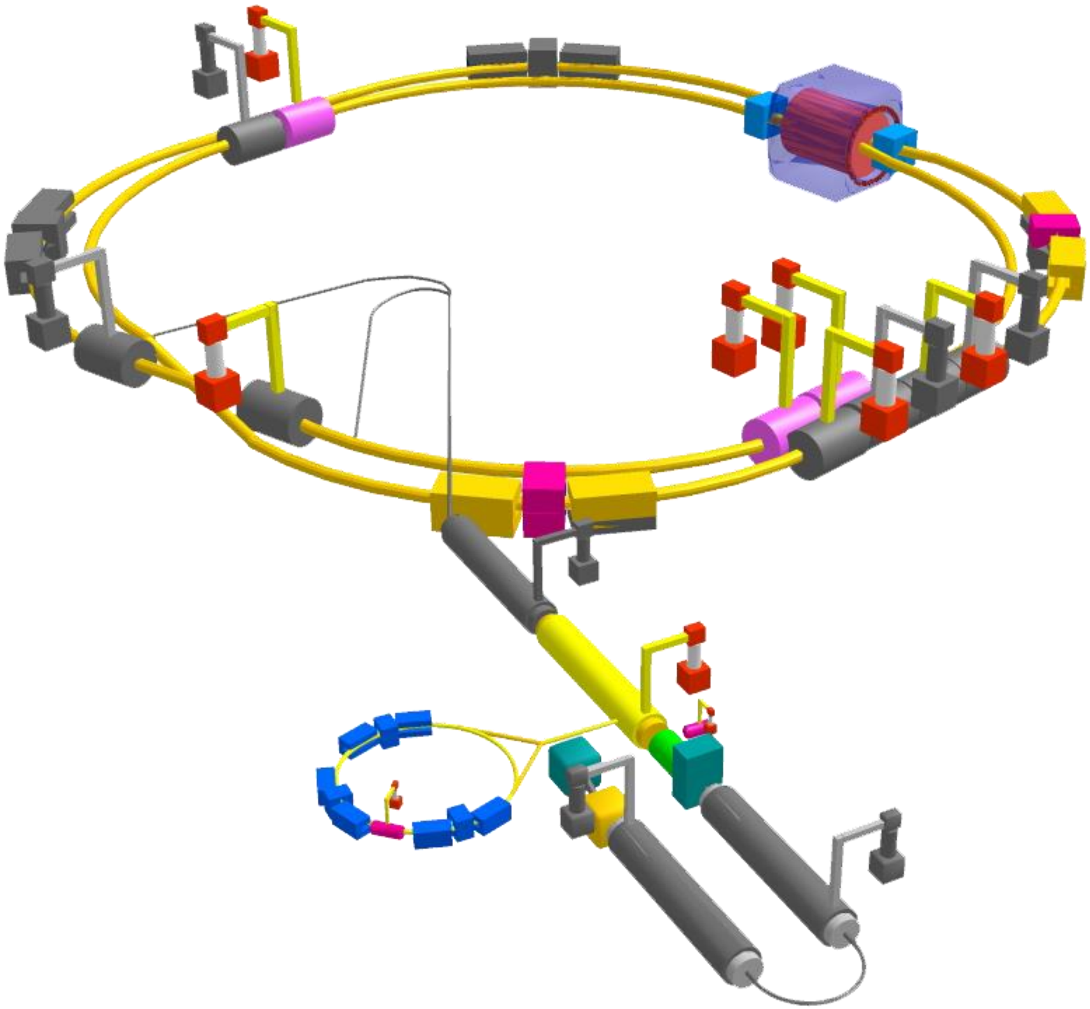
- Noize related lines (8kHz) appears in all the LER FB detectors. RMS noise level has greatly reduced from 30 to 5 counts
- Sharp horizontal spectrum near half integer?? (LERUX) which greatly restricts the tuning range of FIR filter
- Mode coupling related instabilities were not so obvious.

Summary

- **Bunch by bunch feedback systems for SuperKEKB rings are working.**
  - Contributing to suppress the CBI (which could observe less than 30mA of total current)– enabling to store more than 1A with by 2 filling pattern.
  - Feedback noise effect (to enlarge /excite) the bunch in vertical plane has been observed. We have replaced the bunch detector with low NF structure. The rms noise level reduced, as expected.
- **Still observed the luminosity drop with vertical FB gain in LER**
  - Tune the FIR phase/phase shift to suppress excitation.
  - Reduced the V-FB gain.
  - Hunting noise source (RF? Power supplies?)
  - In HER, reducing the V FB gain resulted the increase of vertical beam size and luminosity drop.

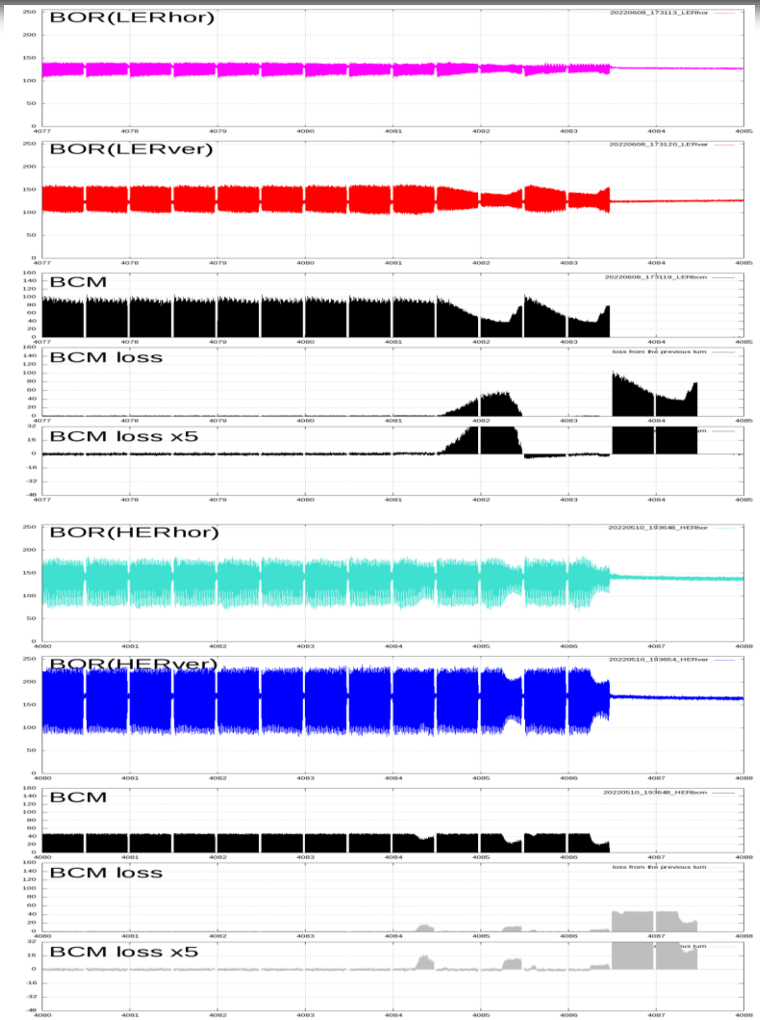
Backup

SuperKEKB accelerators



- Circumference 3km
- LER:e^+ 4GeV 3.6A
- HER:e^- 7GeV 2.6A
- f_{RF}=508.886MHz
- h=5120
- Low emittance 3.2/4.6nm with ~0.28% xy-coupling
- Bunch length 6/5 mm @1mA/bunch
- β* at IP H/V 32/0.27mm 25/0.3mm
- Luminosity ~60x10[35]
  - x30 of KEKB

Sudden beam loss



- **Without growing the transverse motion, some part of bunches drops within 1–2 turns.**
  - Occurs in both LER and HER, but the damage in LER is much greater (QCS quench, vertical collimator damage, etc)
  - After damaging the collimator heads, many unwanted side-effects happen.
    - Much larger background.
    - Larger transverse beam impedance.
- **Several discussions on ITF-sudden beam loss subgroup.**

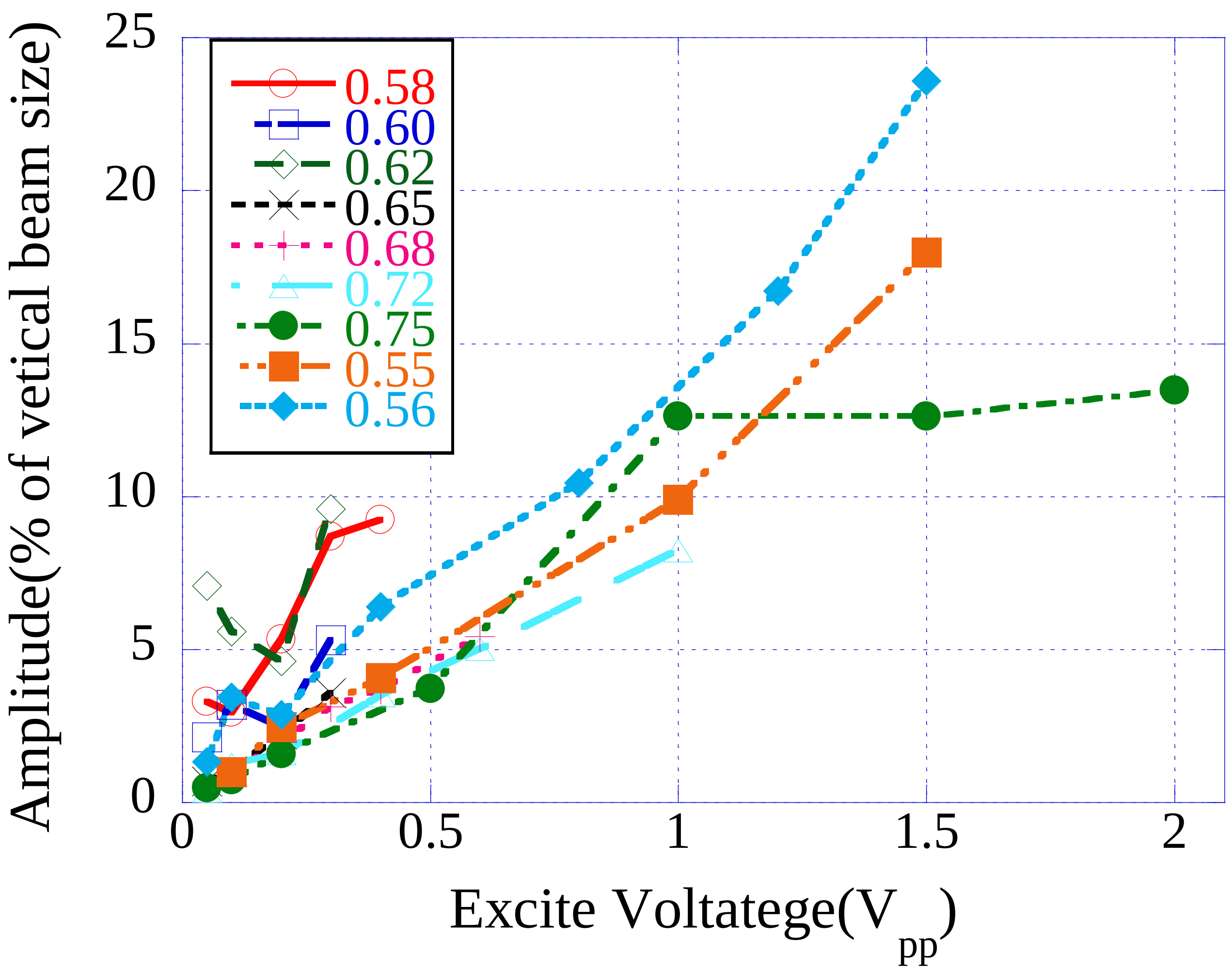
Broadband noise in the FB system (KEKB time)

- **The effect has first observed during the KEKB operation**
  - Final amplifier in the 2GHz phase shifters (all HER and LER) were modified during long maintenance time– the output power had (significantly) increased. This caused the increase of the noise level of the FB detectors (also caused the increase of the feedback power).
  - After the maintenance, the luminosity had decreased.
  - Occasionally, one electrode of LER transverse feedback kicker had failed--- I've turned off one final power amplifier and observed the jumping up of the luminosity (to almost the original luminosity level)!
  - We've adjusted the level of the output of 2GHz phase shifter and lowered the V-FB gain.

Noise effect study at KEKB

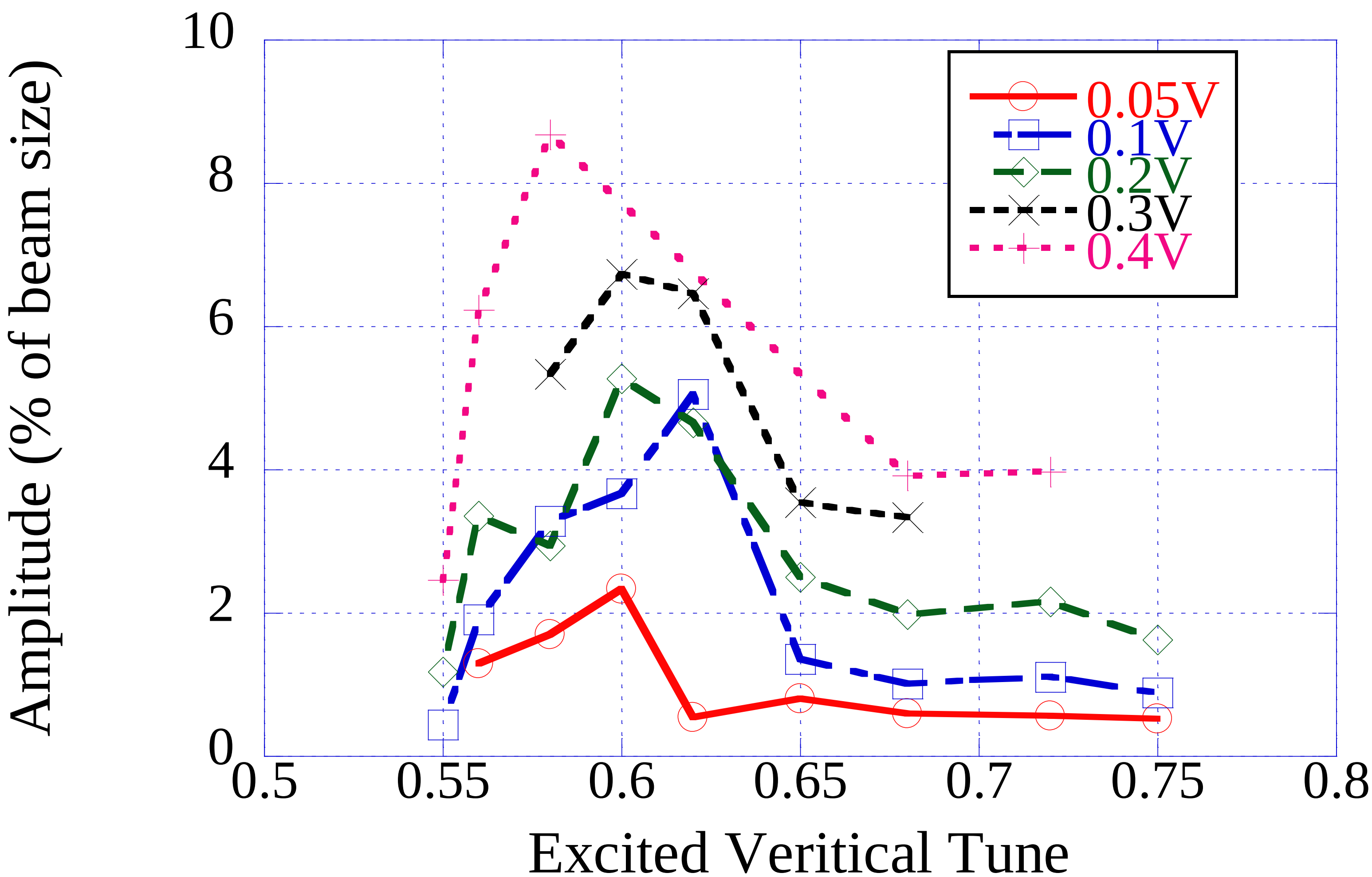
- With the systematic study of the relations between the trans-verse feedback gains and the luminosity, we have found only LER vertical feedback gain affected the luminosity and the vertical beam size; other transverse feedback gain, LER-H, HER-H and HER-V had no obvious relation to the luminosity.
- Though the vertical beam size slowly increased (~10%) with the feedback gain during single-beam condition, it jumped up more than 40% with small change of the feedback gain during collision. The resulting luminosity decreased around 10 to 20% with the blowup of the vertical beam size.
- We have injected pure sinusoidal signals or band-limited white noises from a function generator to the V-FB system. The amplitudes of the excited oscillation of the LER beam were detected with the bunch oscillation recorders (BOR).
- Reported at DIPAC2011 (MOPD73).

Single frequency response (collision) at KEKB LER

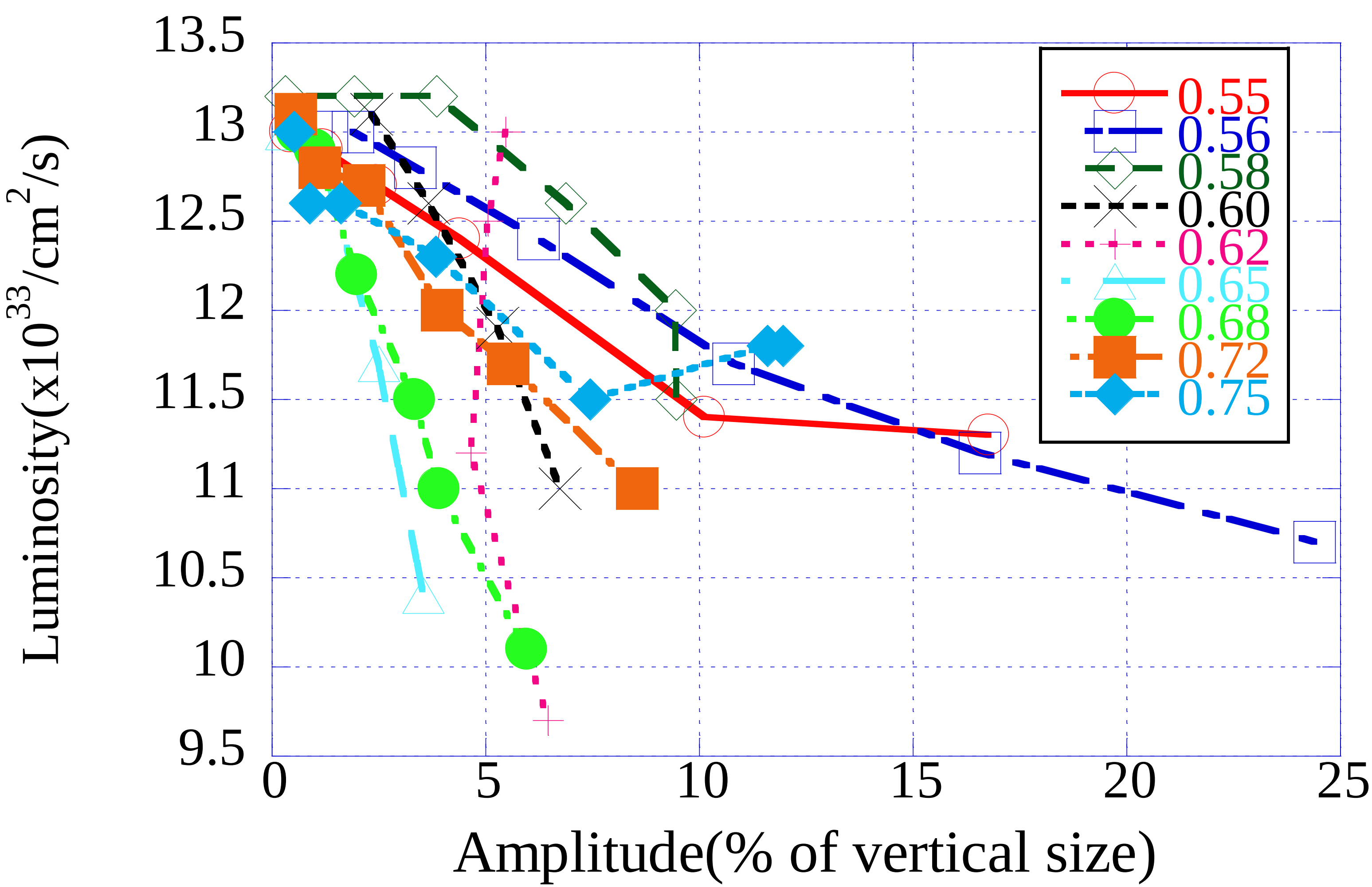


Larger response from tune (0.58) to 0.63 (tune + beam-beam tune shift)

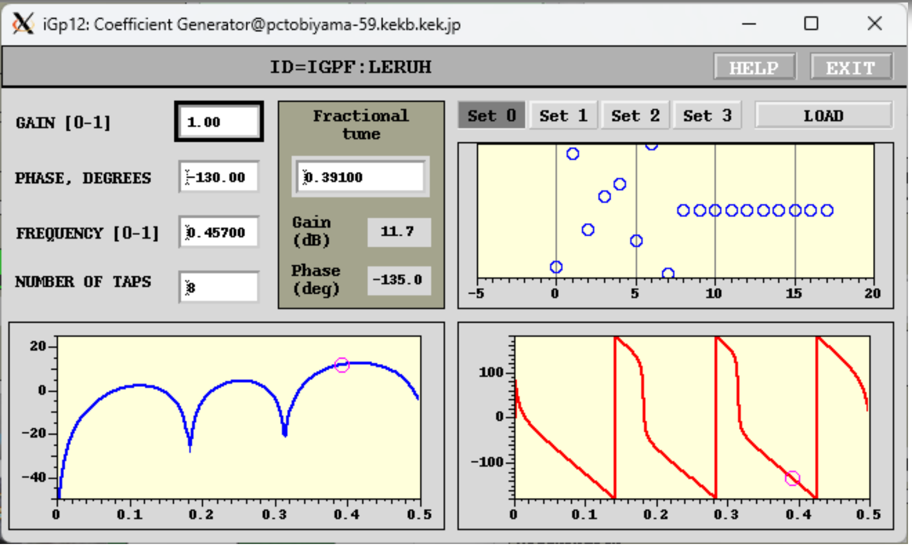
same excitation voltage @ KEKB LER

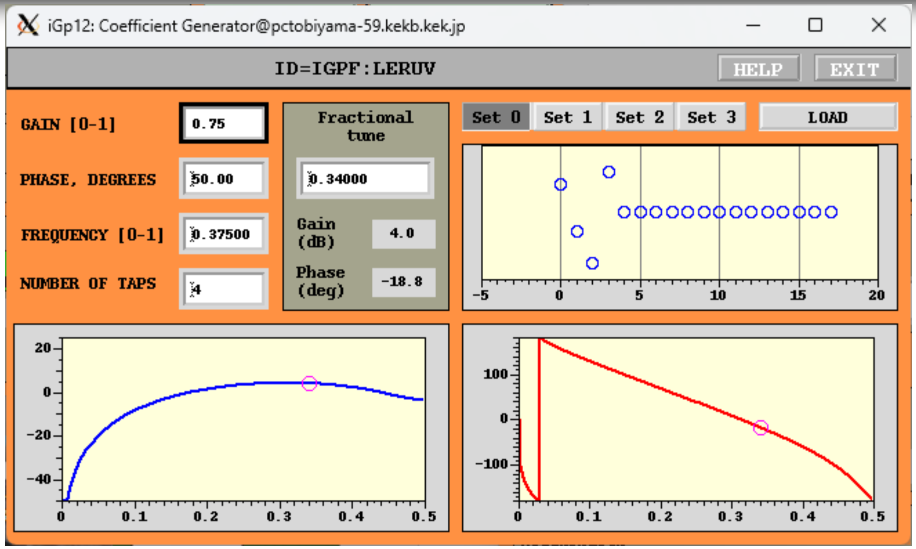


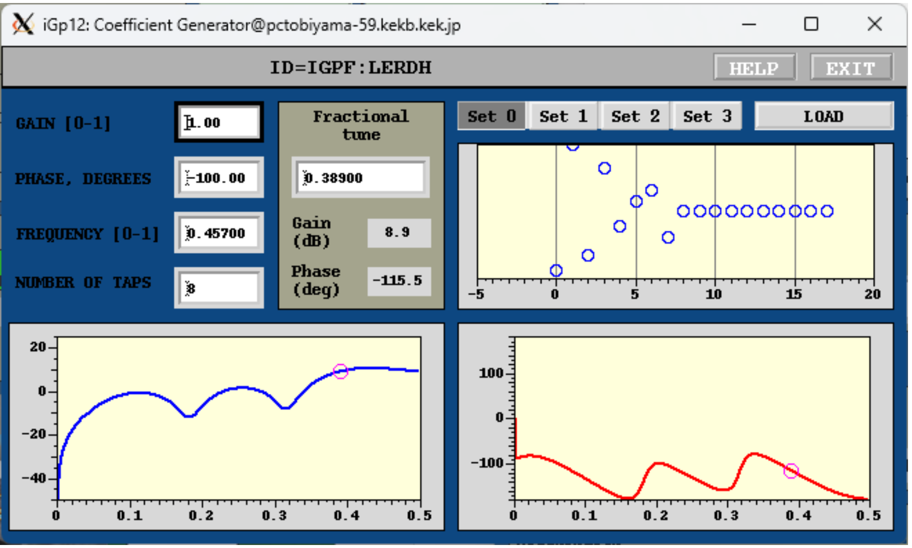
Luminosity drop @ KEKB LER

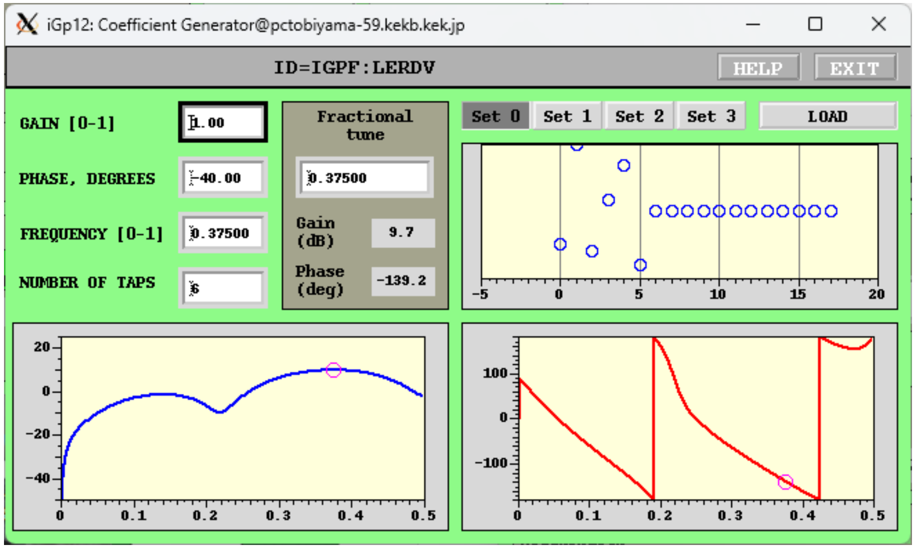


LER Transverse FIR filter

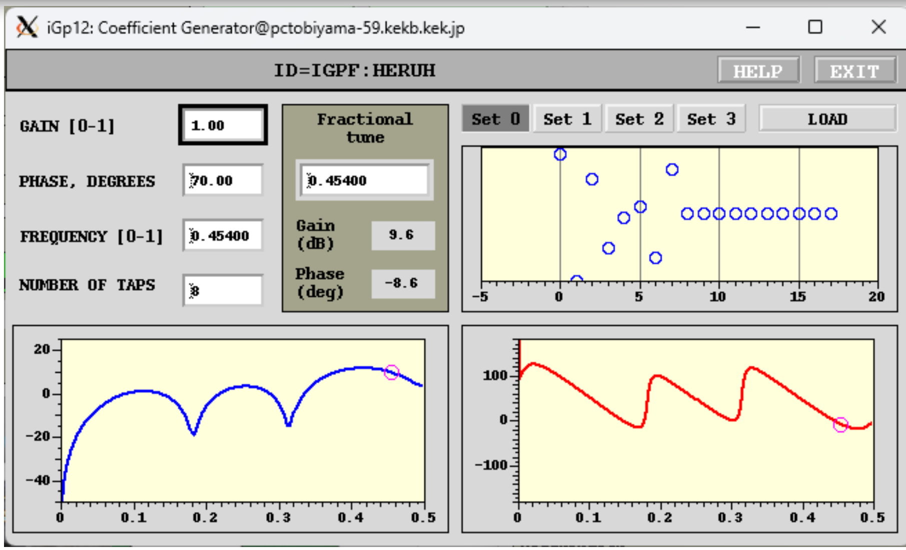


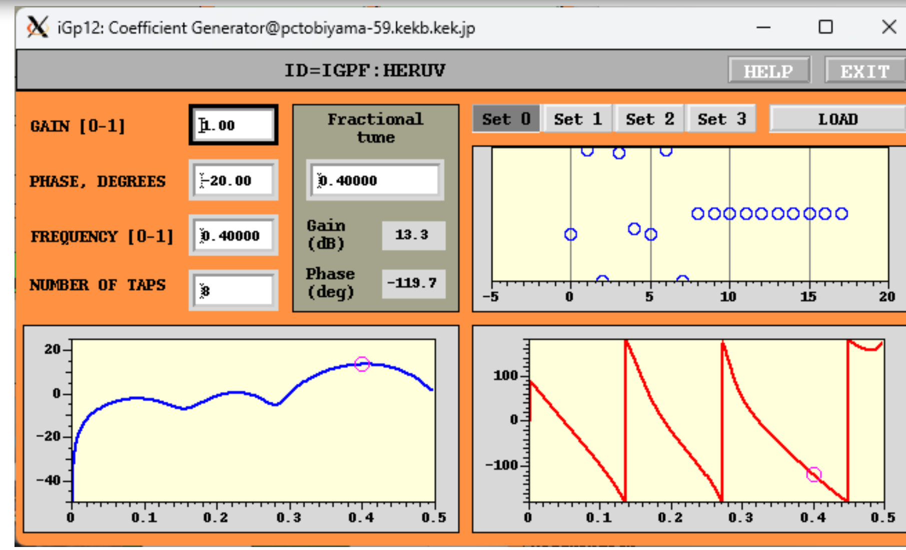


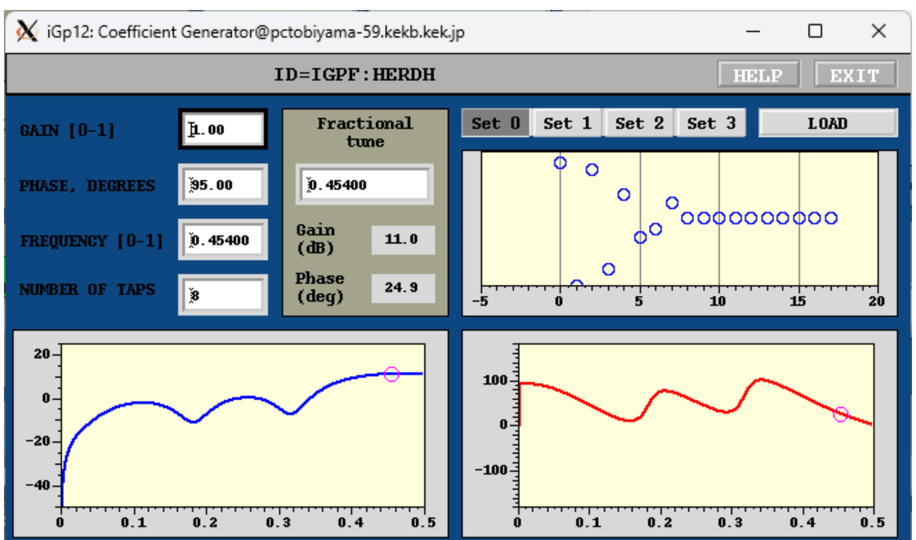


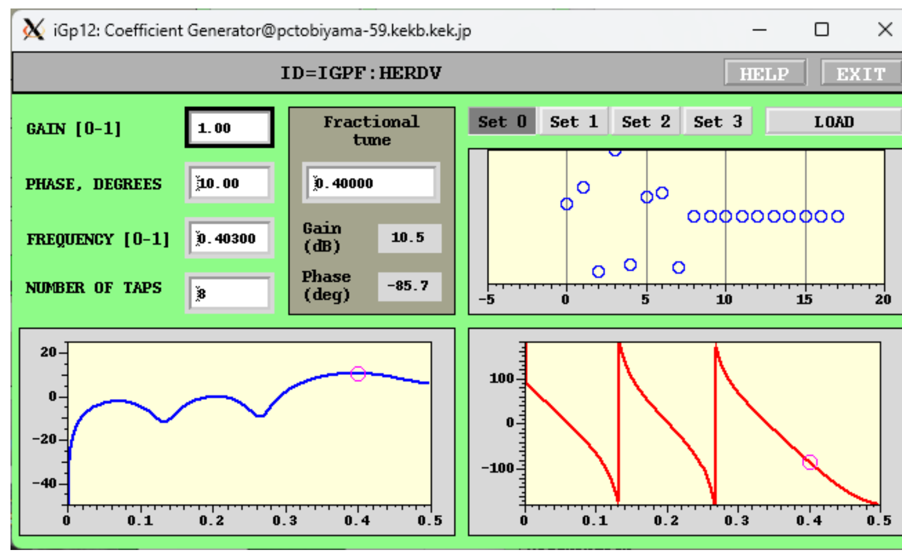


HER Transverse FIR filter

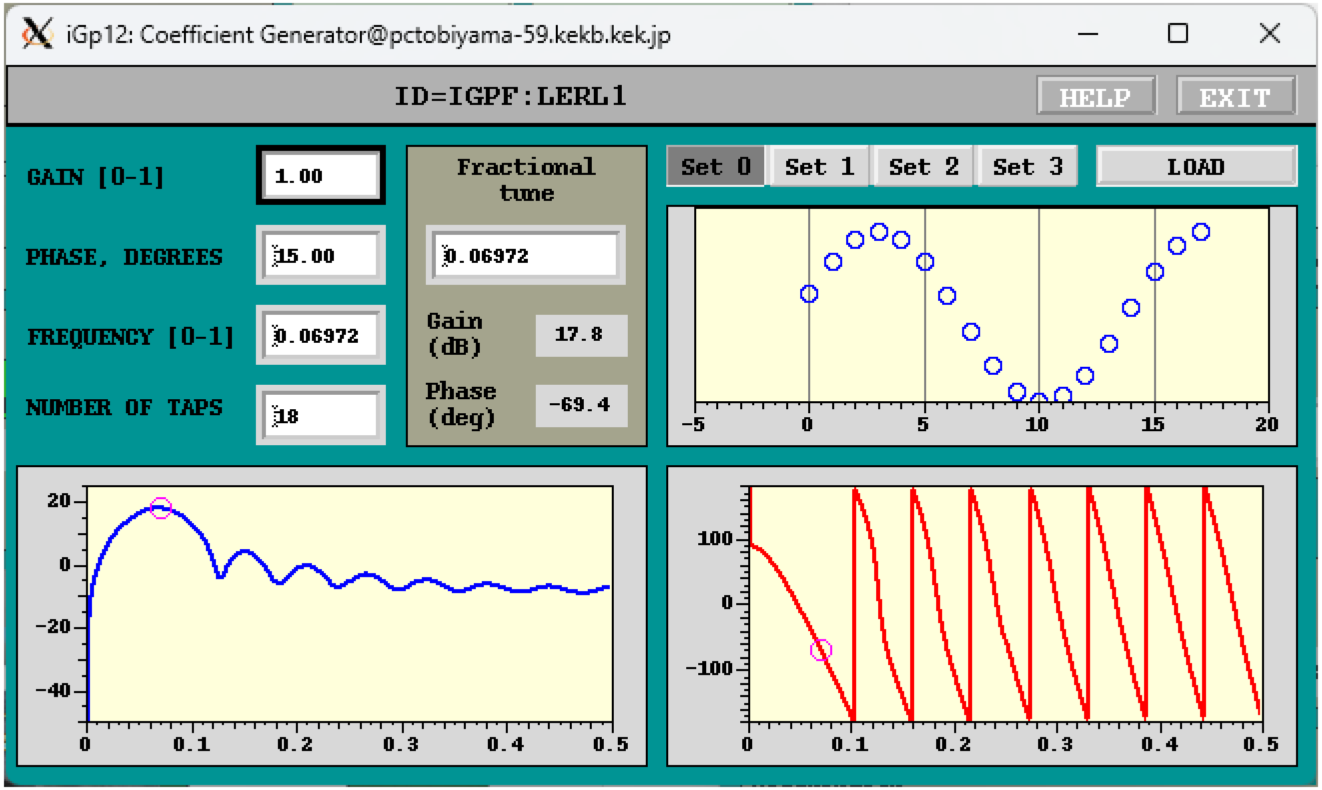




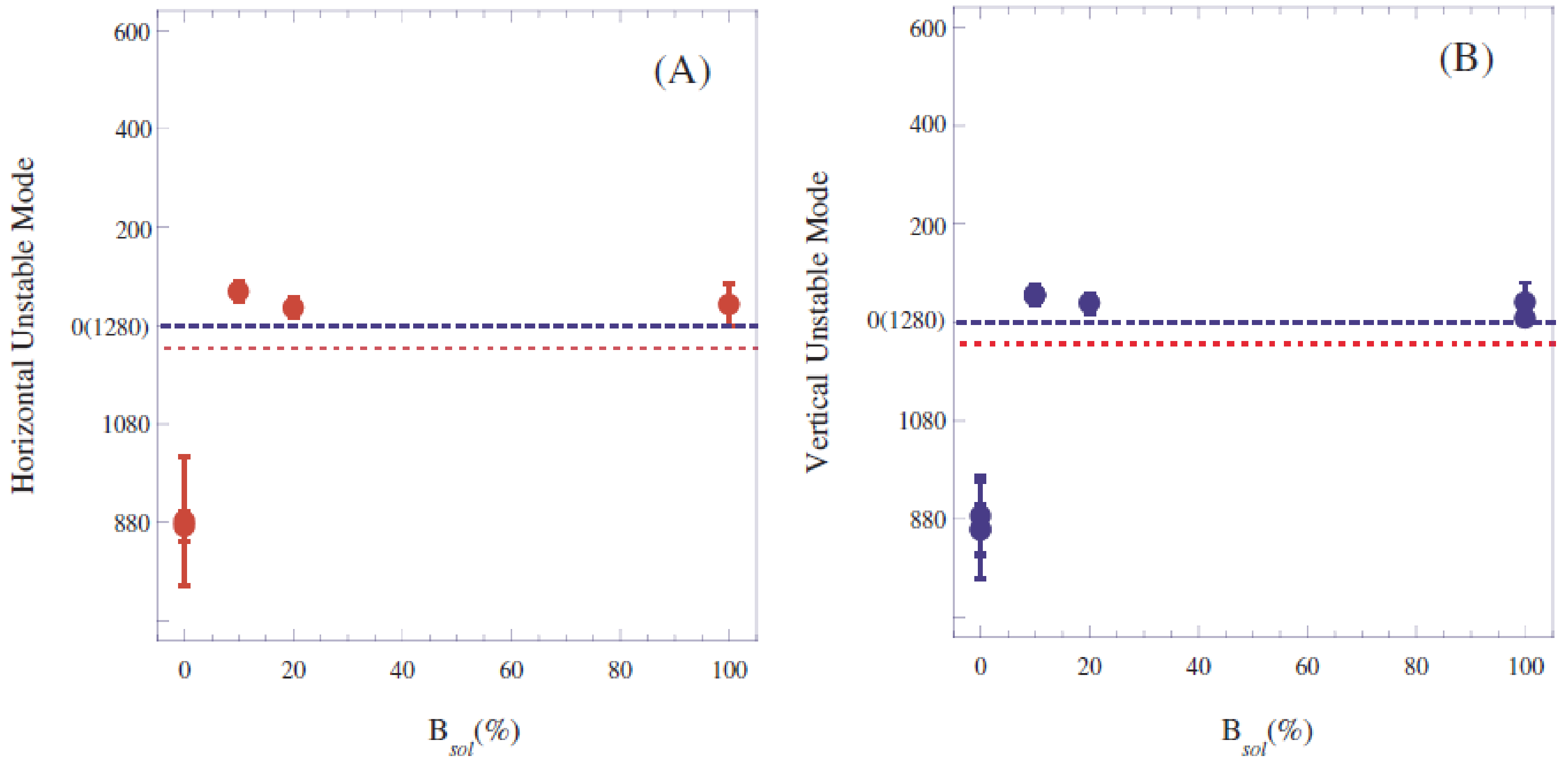




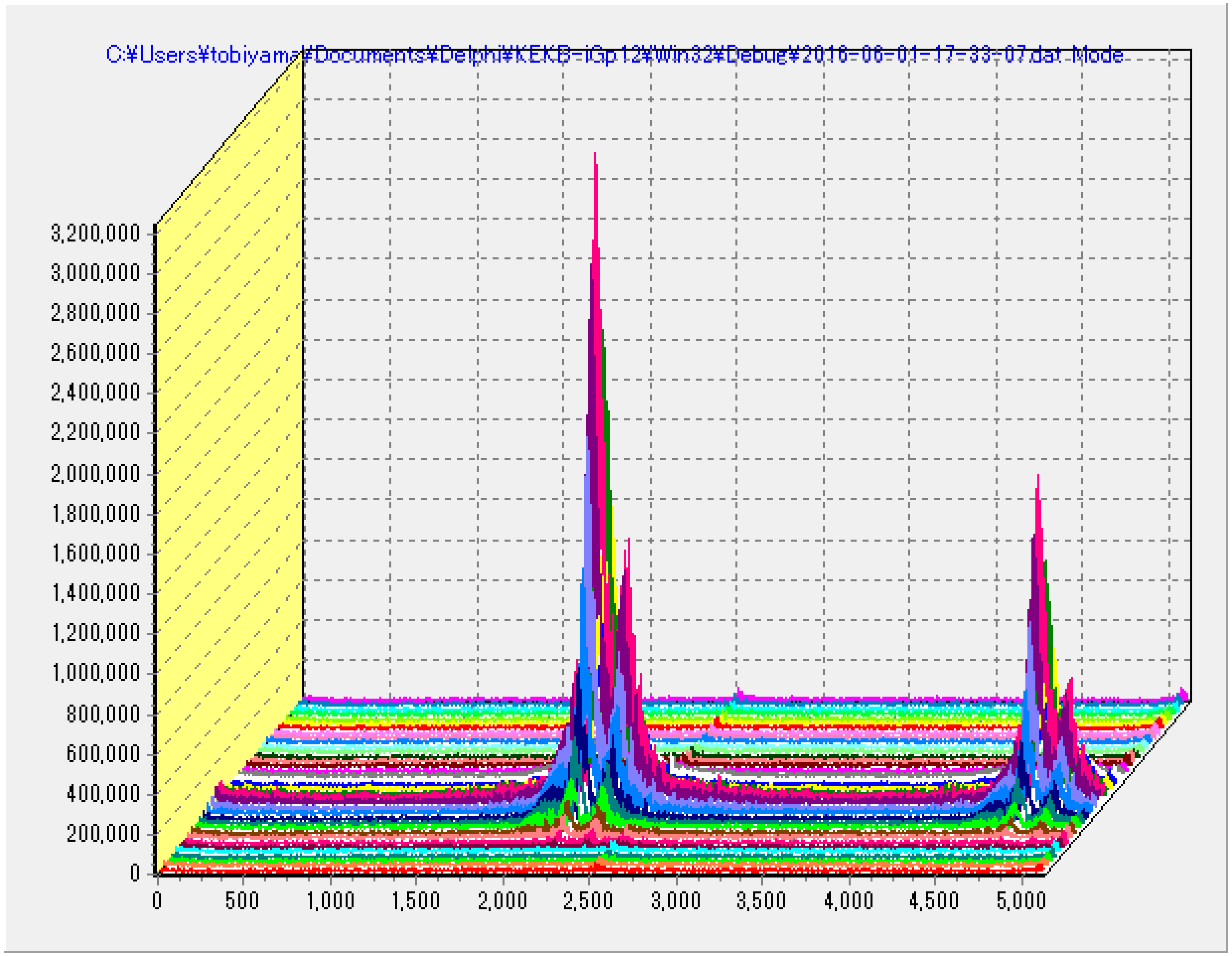
LER Longitudinal



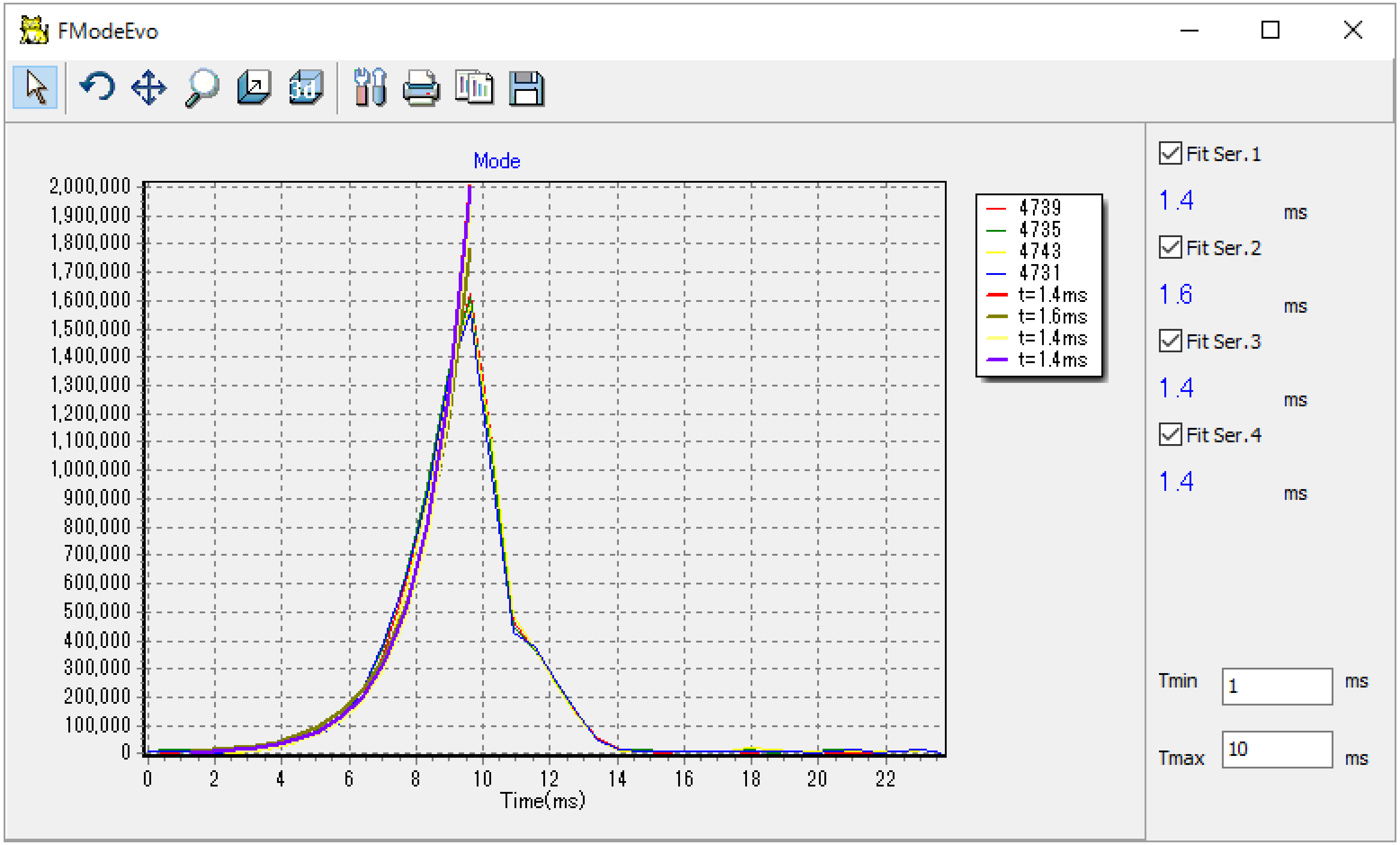
LER ECI Unstable mode



永久磁石設置前の例



By 2, 300mA Vertical方向


FModeEvo
Mode
2,000,000
1,900,000
1,800,000
1,700,000
1,600,000
1,500,000
1,400,000
1,300,000
1,200,000
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
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0
2
4
6
8
10
12
14
16
18
20
22
Time(ms)
4739
4735
4743
4731
t=1.4ms
t=1.6ms
t=1.4ms
t=1.4ms
Fit Ser.1
1.4
ms
Fit Ser.2
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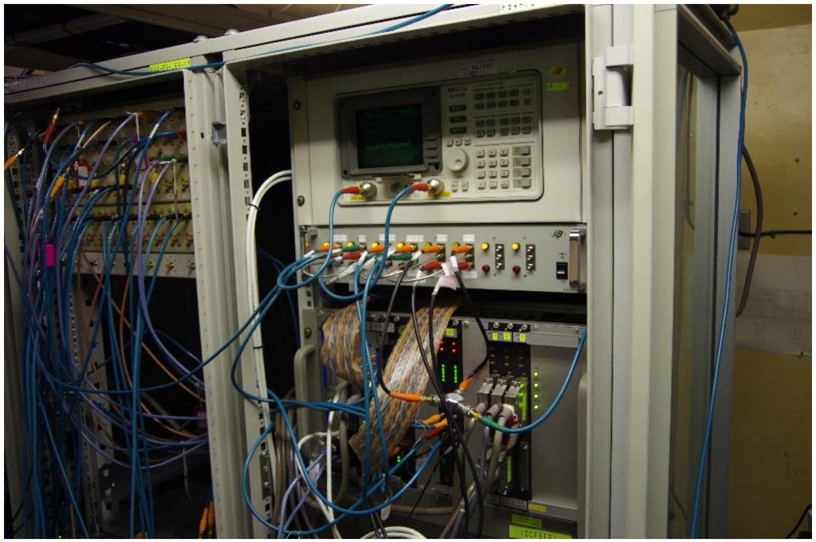
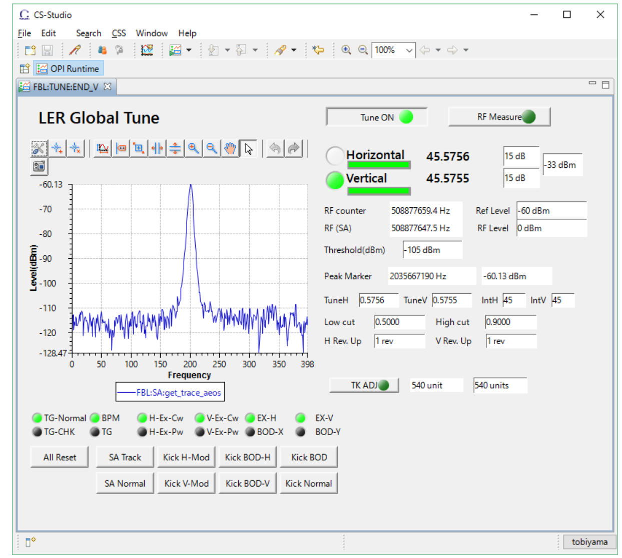
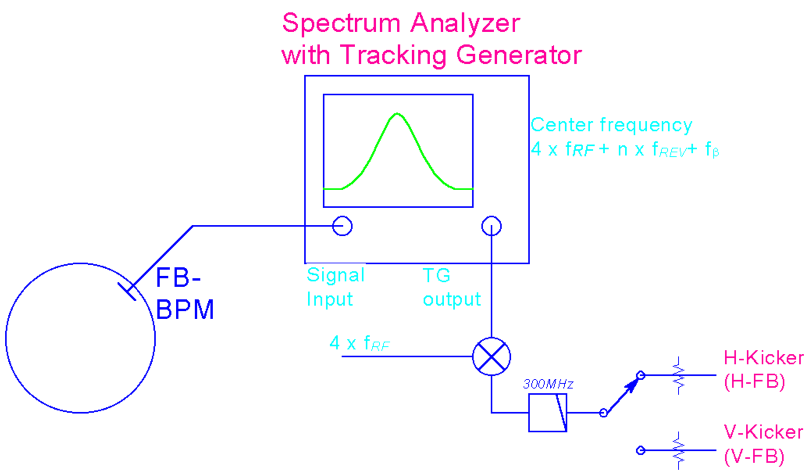
ms
Fit Ser.3
1.4
ms
Fit Ser.4
1.4
ms
Tmin
1
ms
Tmax
10
ms

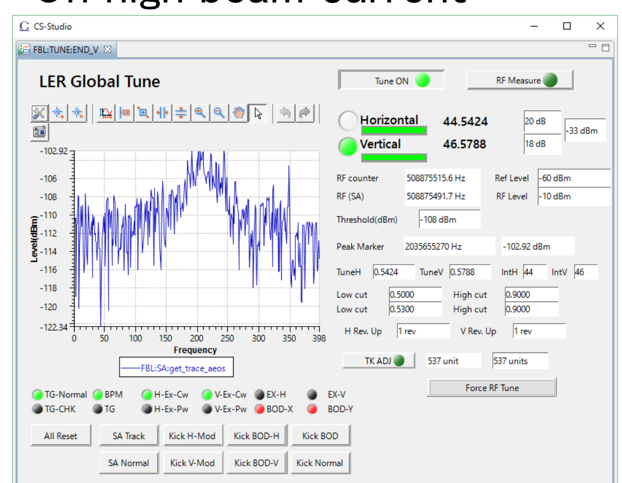
Betatron tune monitor (1)



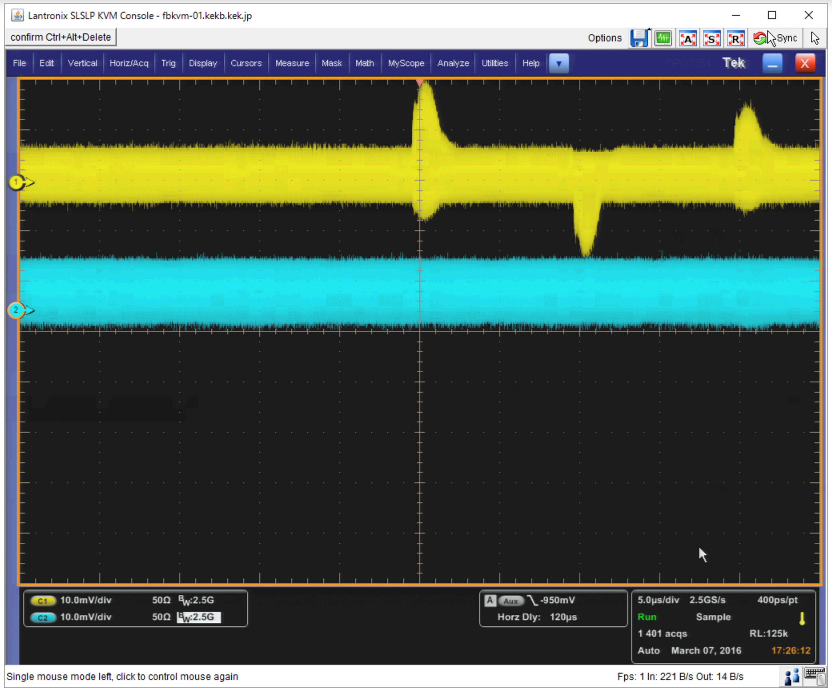


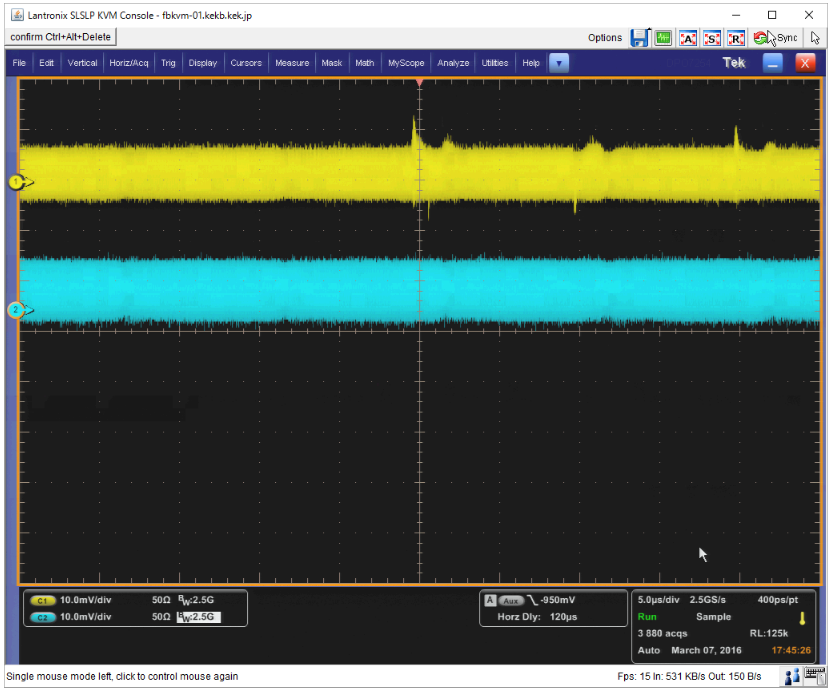


On high beam current



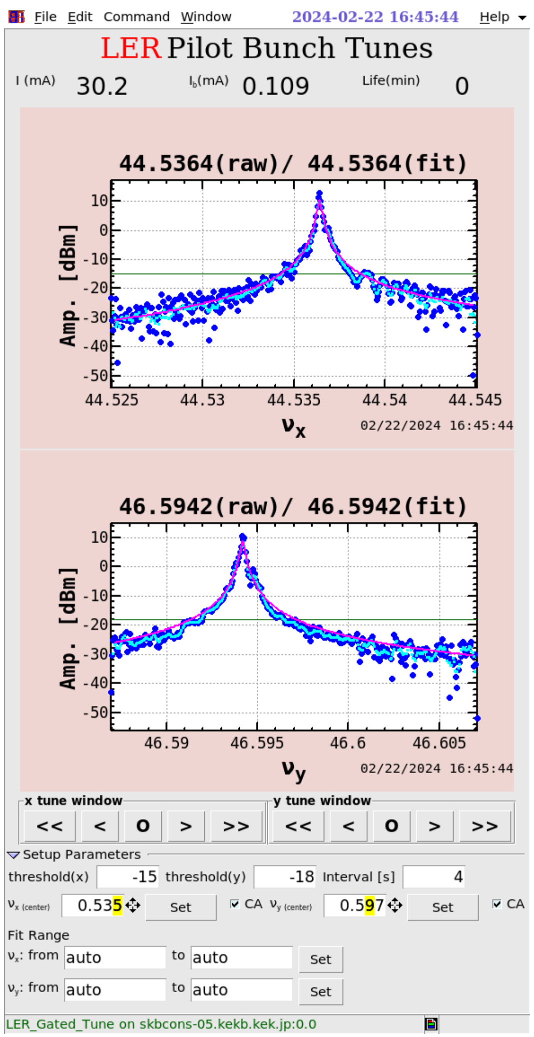
Example of direct use of FB detector signal





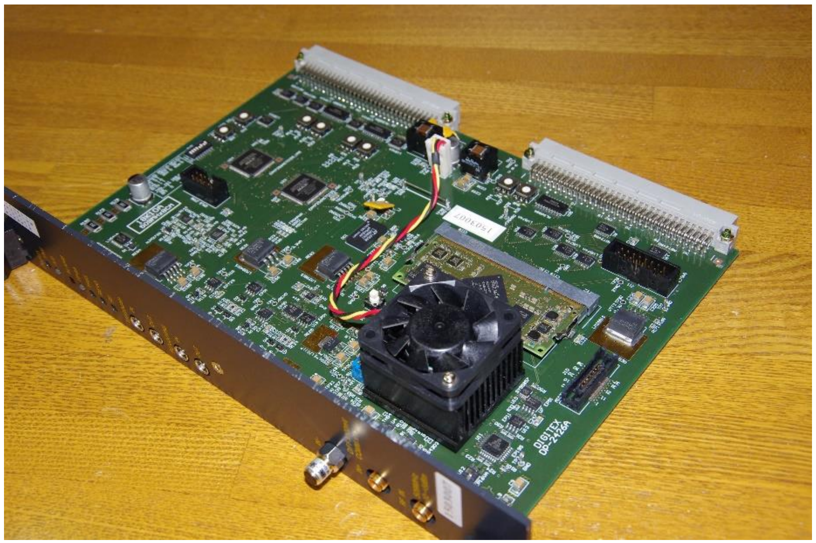
Observe FB signal using wideband oscilloscope– useful to tune the residual of injection kicker bump

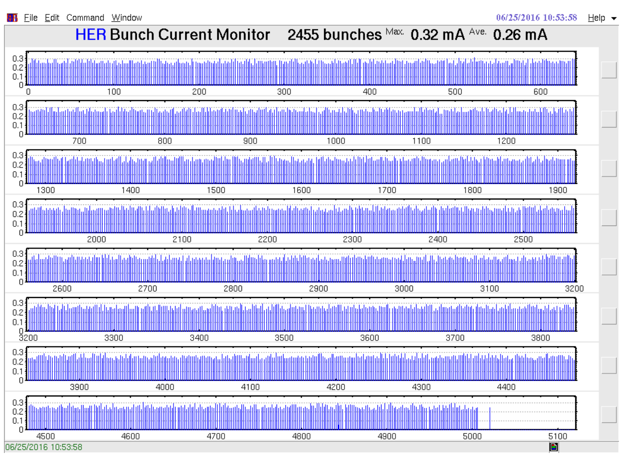
Betatron tune monitor using non-colliding bunch (pilot bunch)



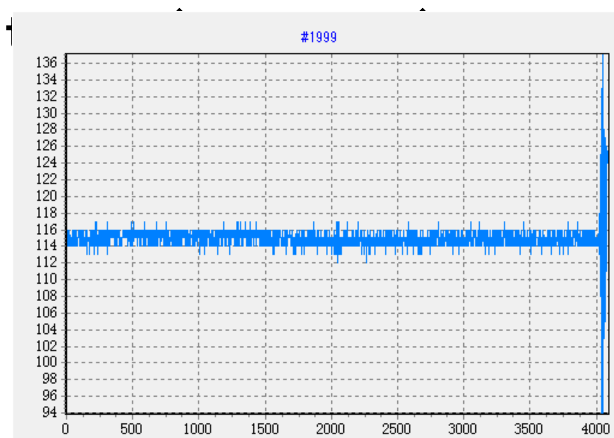
Non-colliding bunch (pilot bunch) to measure betatron tune

Bunch current monitor





- Longitudinal (intensity) detection using same L-FB detection circuit
- MAX108 8-bit ADC/Spartan6 FPGA capable to store more than 80MB(BOR) data.
- Transfer bunch current data to bucket selection system using reflective memory (VME) synchronized with injection



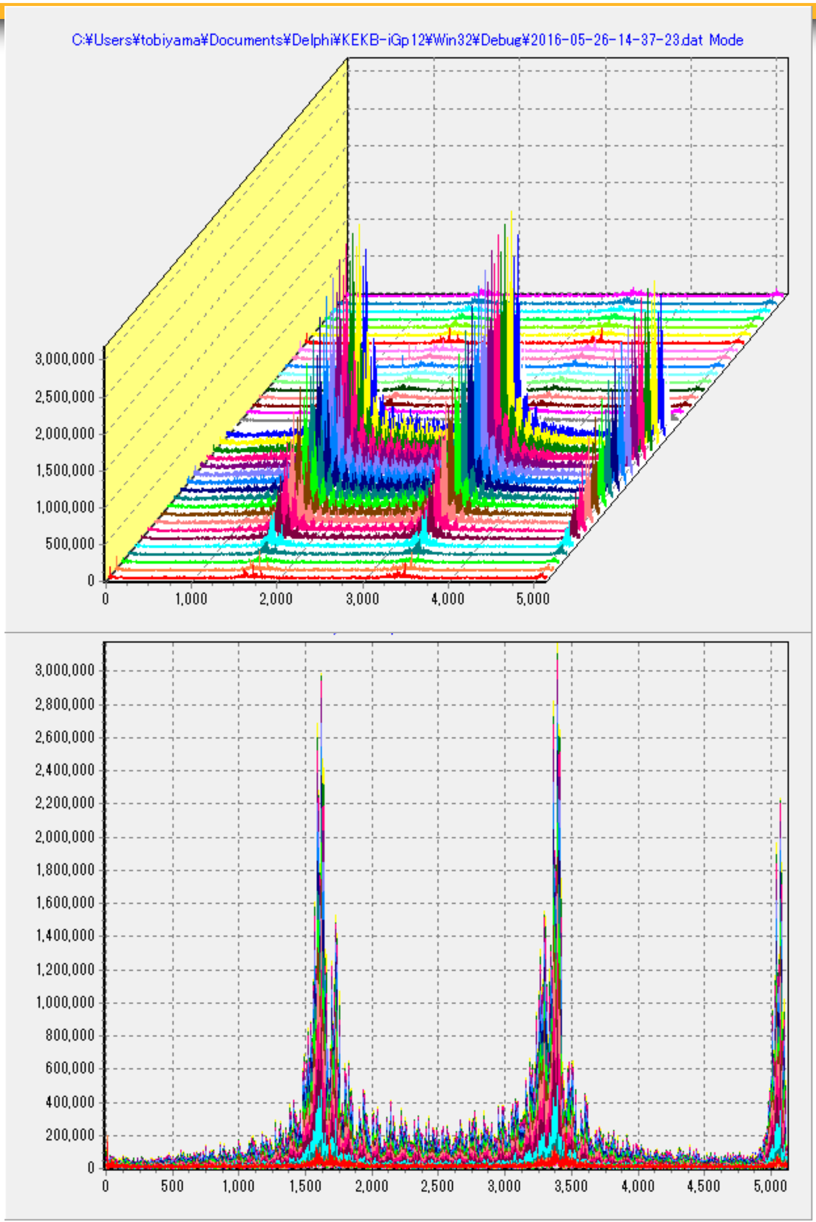
Transient-domain analysis

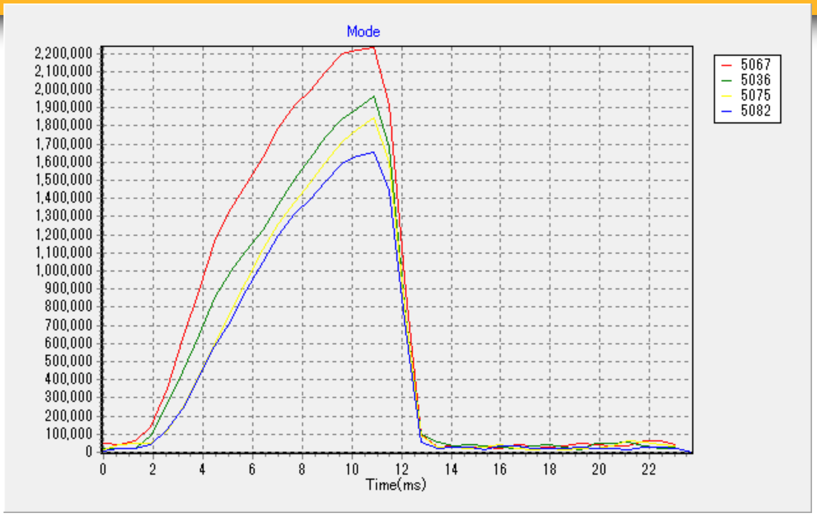
- **Open the feedback loop (few ms) and re-capture the oscillation by closing the loop.**
  - Could observe the "clean" unstable modes and their growthrate.
  - Understand the feedback damping rate.

Mode analysis

- Make FFT of base 5 for the oscillation data of 256 turns (5120 bunches x 256 data points) to obtain the whole spectrum.
- Extract amplitude of the spectrum that corresponds to the betatron frequencies (fb+m x frev), where m represents the mode of the oscillation.
- Align the amplitude by increasing order of the mode-id.
- Repeat the above the procedure while adavancing the starting-point of the data by 128 turns.

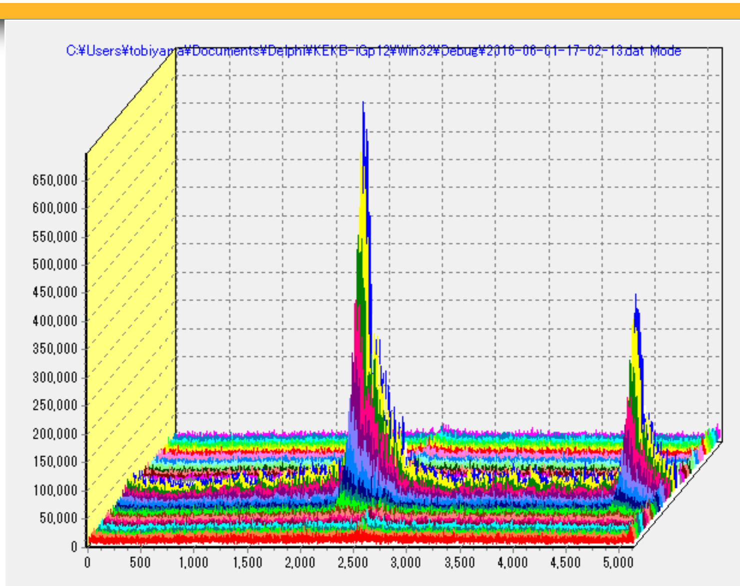
G-D example for HER (e- 7GeV)

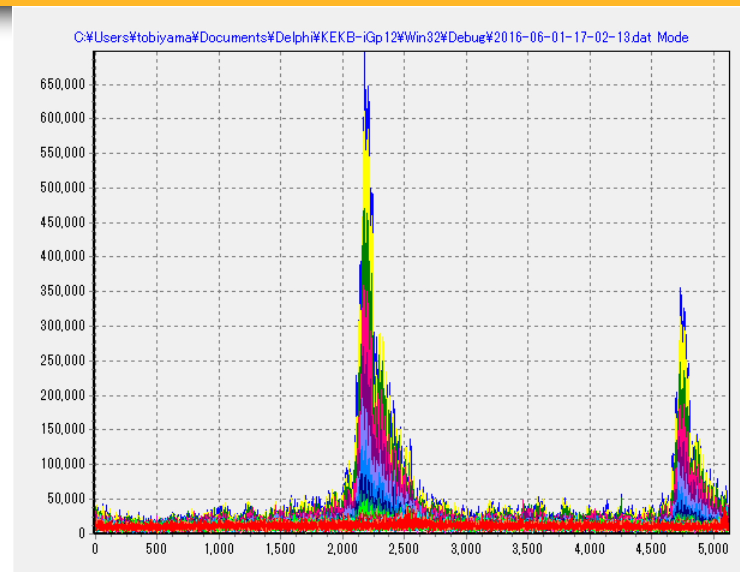


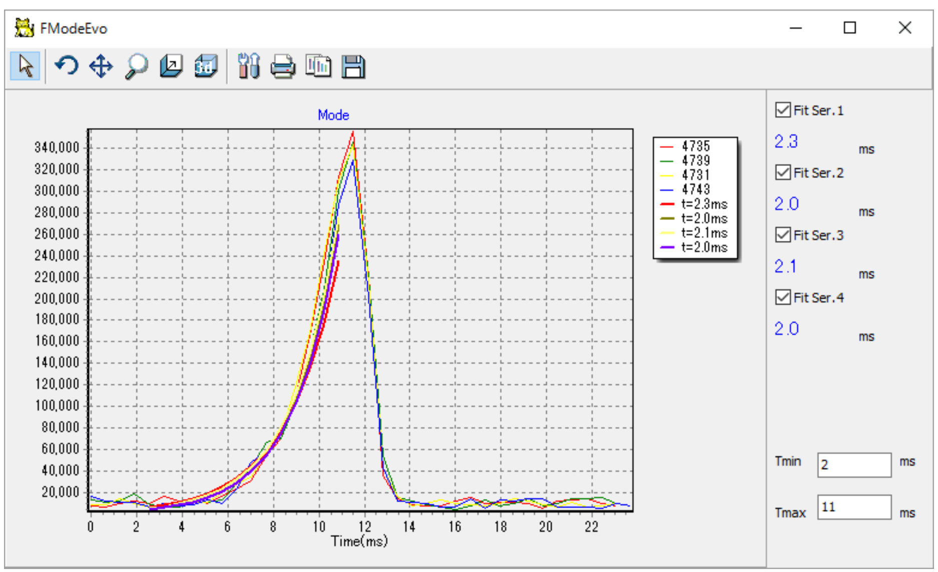


8 Tap FIR filter
732mA, by 3 filling, 0.5mA/bunch
Vertical
Growth~0.9ms
FB damping~0.5ms

Example of by 2 LER vertical (200mA)

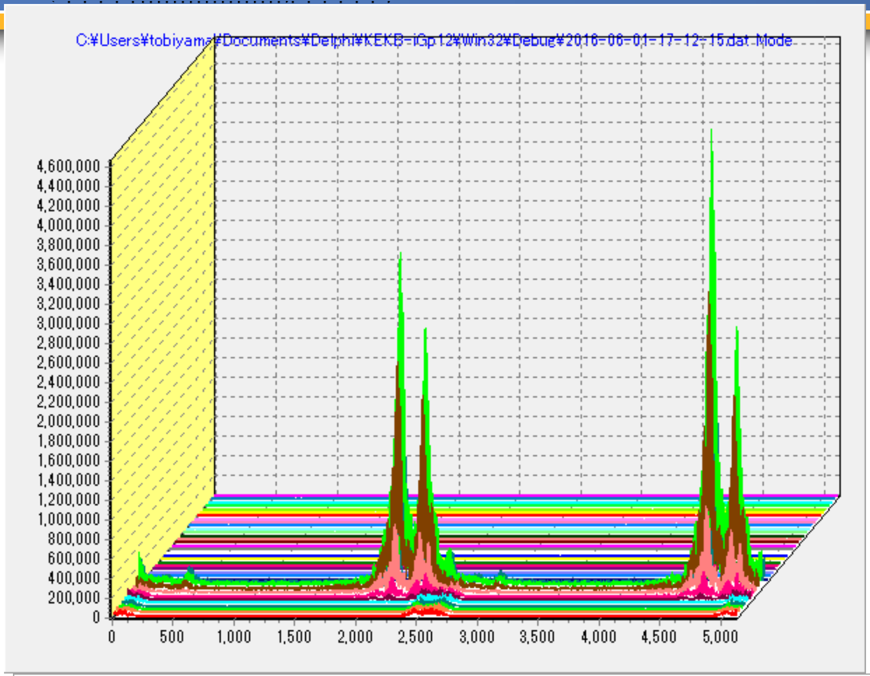


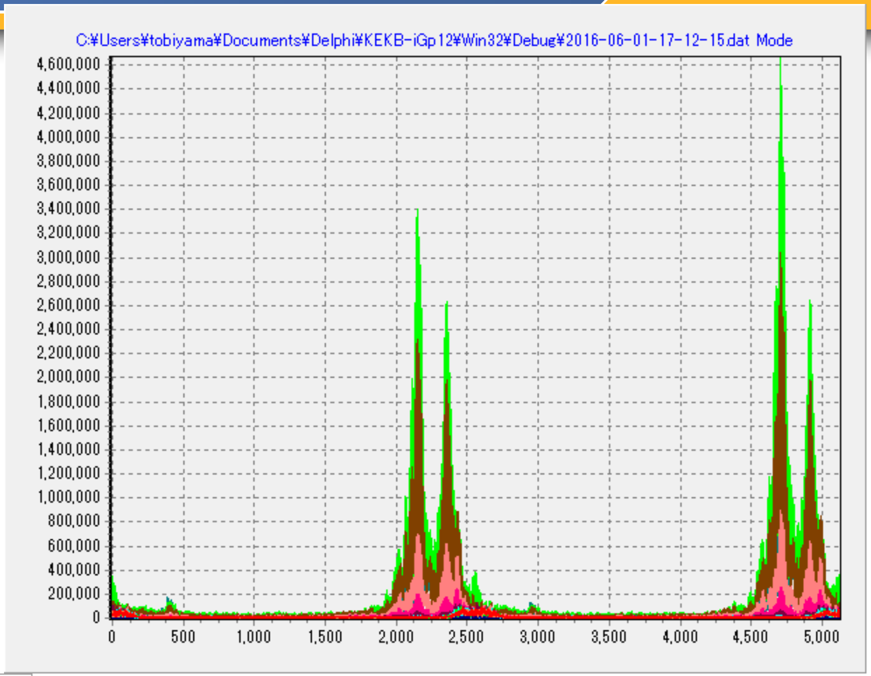


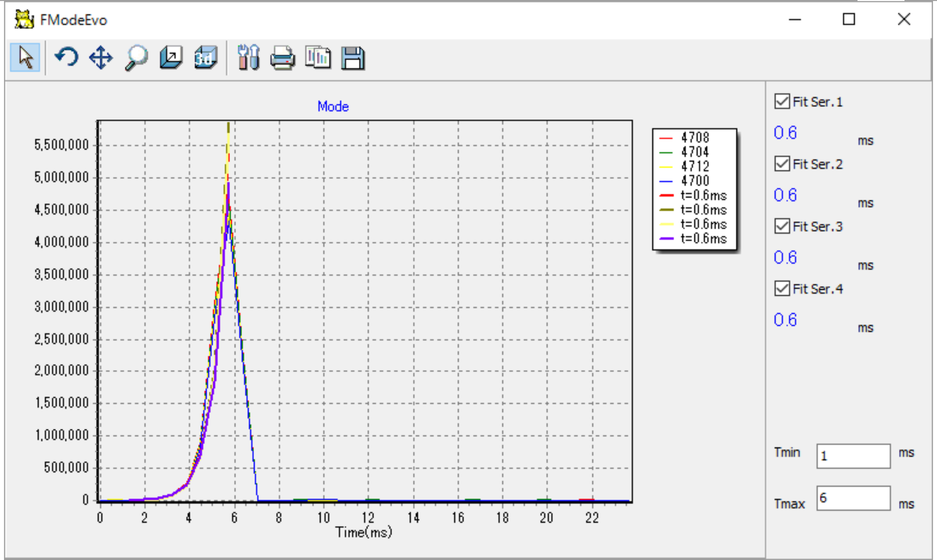


By2 200mA Vertical
Growth time˜ 2.0ms
Damp < 0.5ms

By 2 (300mA) LER Horizontal

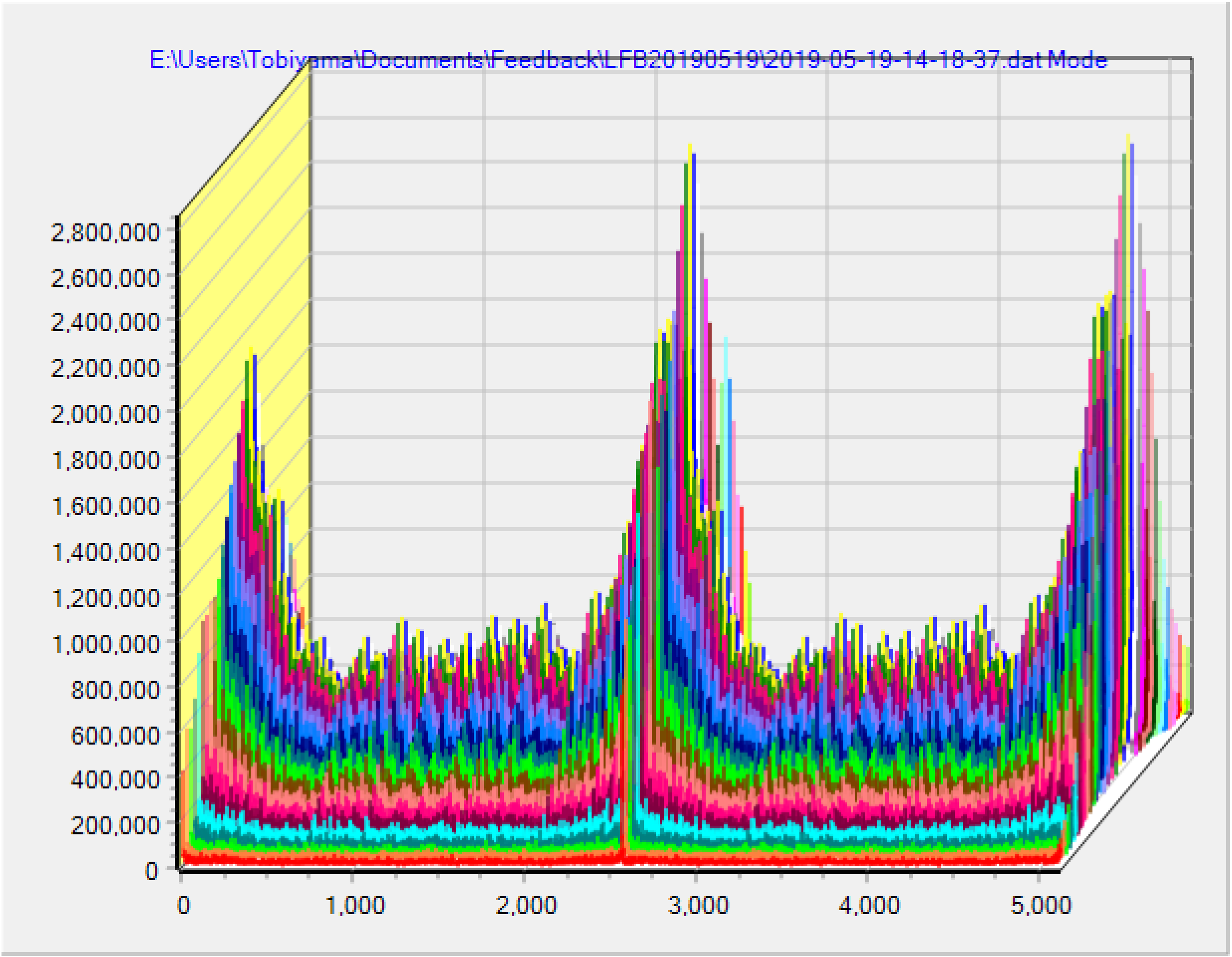






By 2 Horizontal mode
Growth ~ 0.6ms
Damp < 0.5ms

Longitudinal plane



Excite-damp (by 2 pattern, 500 mA)

LFB Gain and damping rate