Performance Evaluation of the Intra-Bunch Feedback System at J-PARC Main Ring

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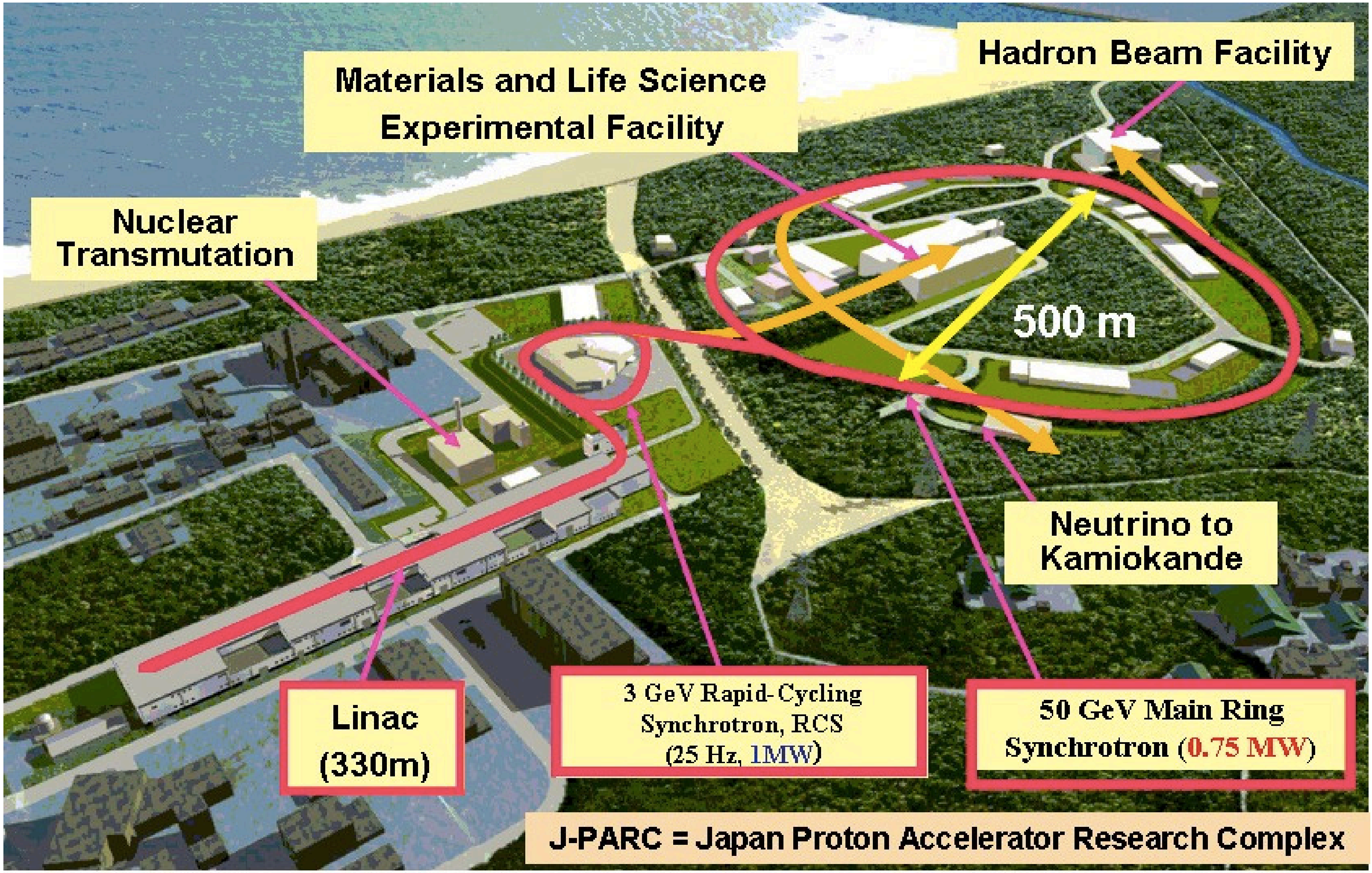
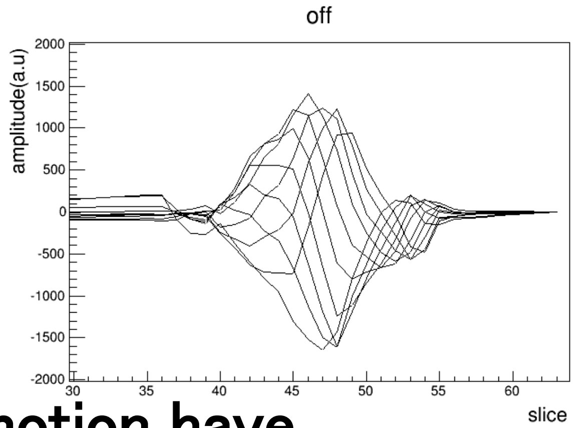
J-PARC Accelerator complex



J-PARC MR parameters

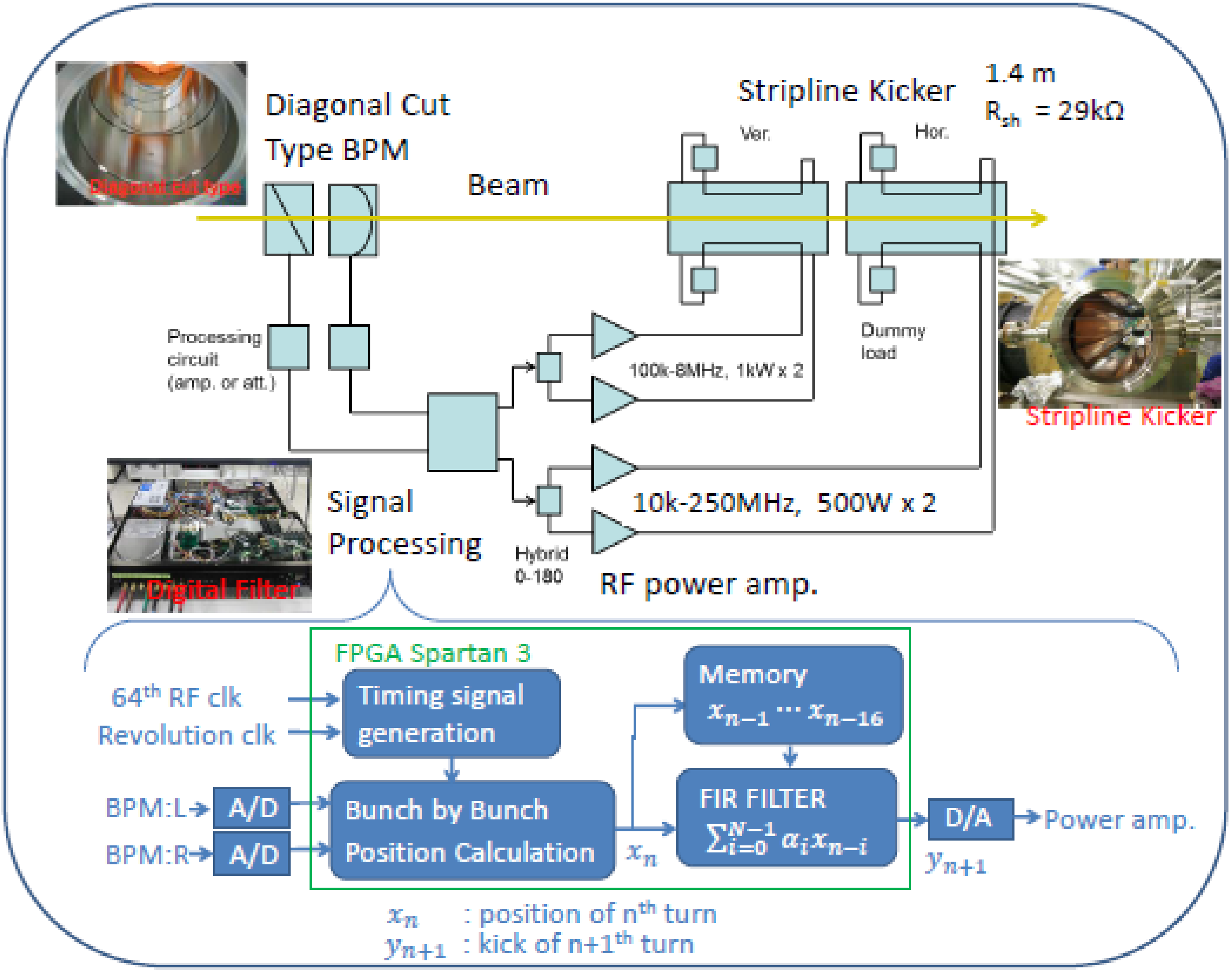
- Circumference 1567.5 m
- Injection Energy 3 GeV
- Extraction Energy 30 GeV
- Revolution at injection 5.384us(185.7kHz) RF 1.67MHz
  at extraction 5.231us(191.2kHz) RF 1.72MHz
- Harmonic number 9
- Repetition time for fast extraction 2.5 s



At high beam power

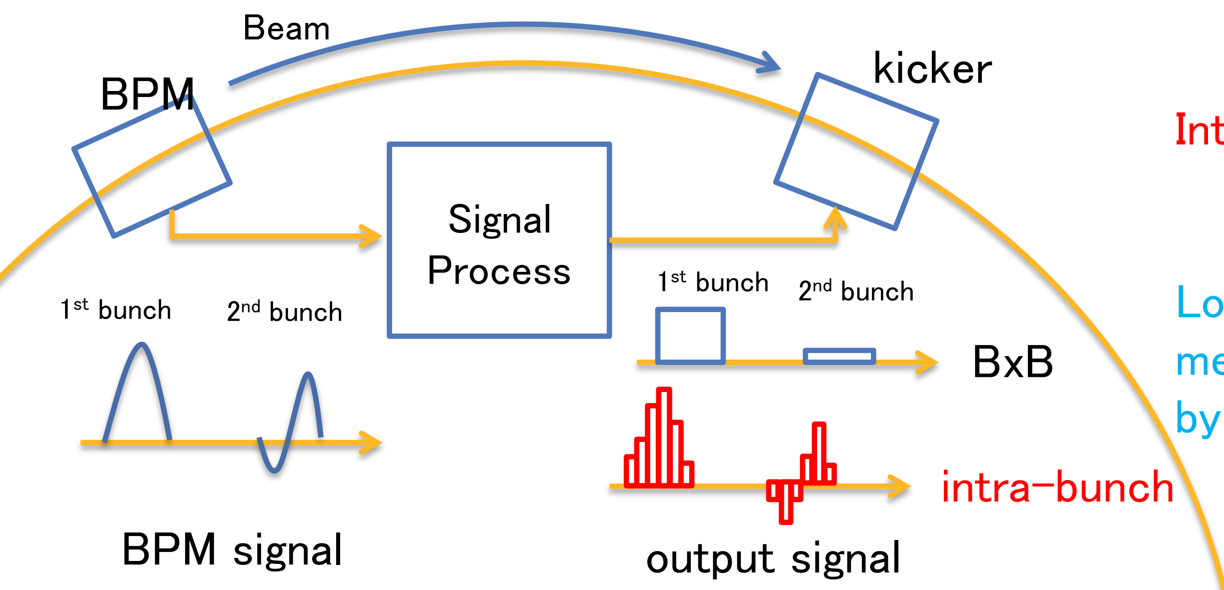
- Coupled bunch instability & intra-bunch motion have been observed which (partly) limited the beam power (due to beam loss).

Bunch by bunch Feedback system



Intra-bunch Feedback System in J-PARC MR

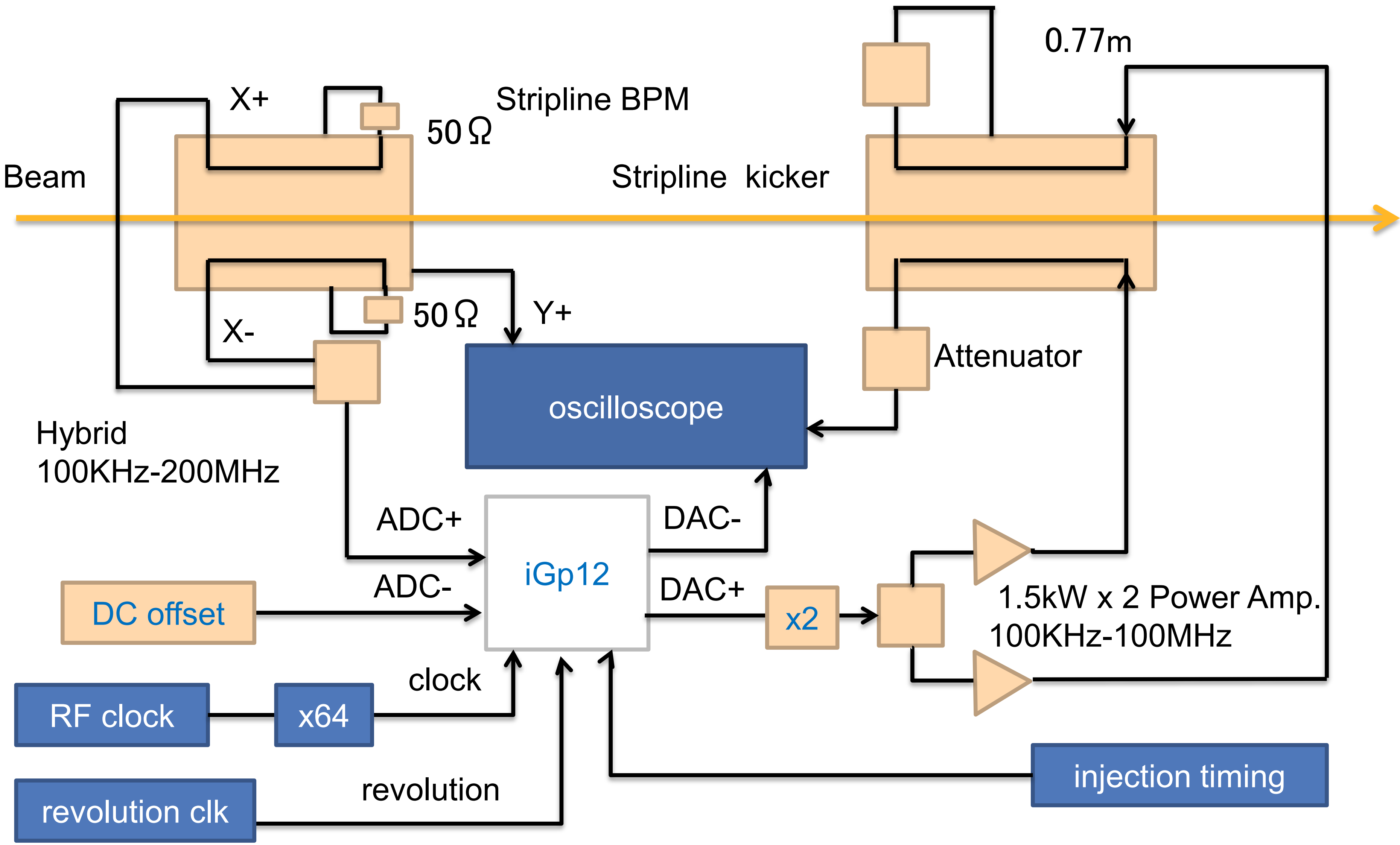
- **Bunch by bunch(BxB) feedback systems have successfully suppress instabilities and contributed to increase beam power.**
- **Internal bunch motions are observed –**
  - Might be causing additional instabilities.
  - Intra-bunch feedback could have larger (stable) feedback gain than BxB-FB.



Intra-bunch feedback with
64 slices in one bucket
Slice-by-slice feedback

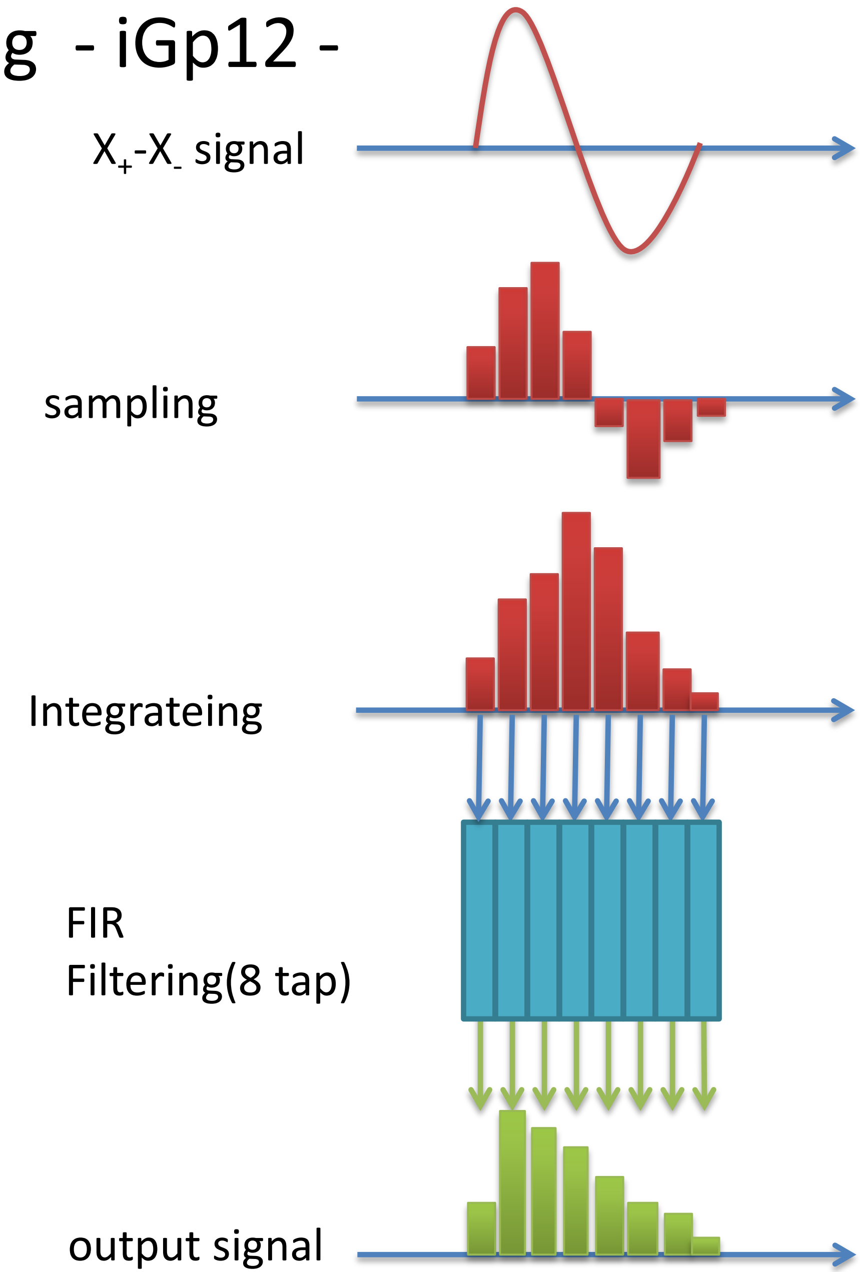
Longer slice-by-slice position memory in FB signal processor by iGp12 (12M samples)

Transverse intra-bunch feedback system -schematic view-



Signal processing - iGp12 -

- Clock frequency = 108MHz (f_{RF}x64).
- Before filtering, the BPM singals are integrated to reconstruct beam position.
- FIR filter (1 ~ 32 tap FIR) + shift gain.
  - 8 tap FIR / 4 tap FIR
  - Parameter table of filter selection, timing (FID delay and Back-end delay), shift gain changes with the external hardware trigger



Feedback Tuning

- **Delay timing**
  - FID delay: By monitoring the beam signal
  - Backend timing: Add excitation signal from iGp12 (center slice) and check the kicker output (beam and excitation signal) by an oscilloscope
  - During acceleration: Need to tune FID, Backend timing (+gain)
- **FIR filter phase**
  - Observe the beam behavior with several FIR filter phase (stable or unstable)
  - Should be checked by the grow-damp experiments.
- **Shift gain (digital feedback gain)**
  - Check the maximum stable gain at good FIR filter phase

Main Beam Parameters

	Beam test	Operation
Circumference	1568m	
Energy	3GeV	3-30GeV
Beam Power	0.5 kW (3 GeV)	230kW (30GeV)
RF Frequency	1.67 MHz	1.67-1.72MHz
Number of bunches	1	8
Synchrotron tune	0.0017	0.002-0.0001
Betatron tune (hor./ver.)	22.41/20.75	
Intensity (/pulse)	$2.7x10^{12}$	$1.3x10^{14}$
Bunch length	150-200 ns	50-200 ns
Chromaticity (hor./ver.)	+0.5/+1.2	-4 – -1

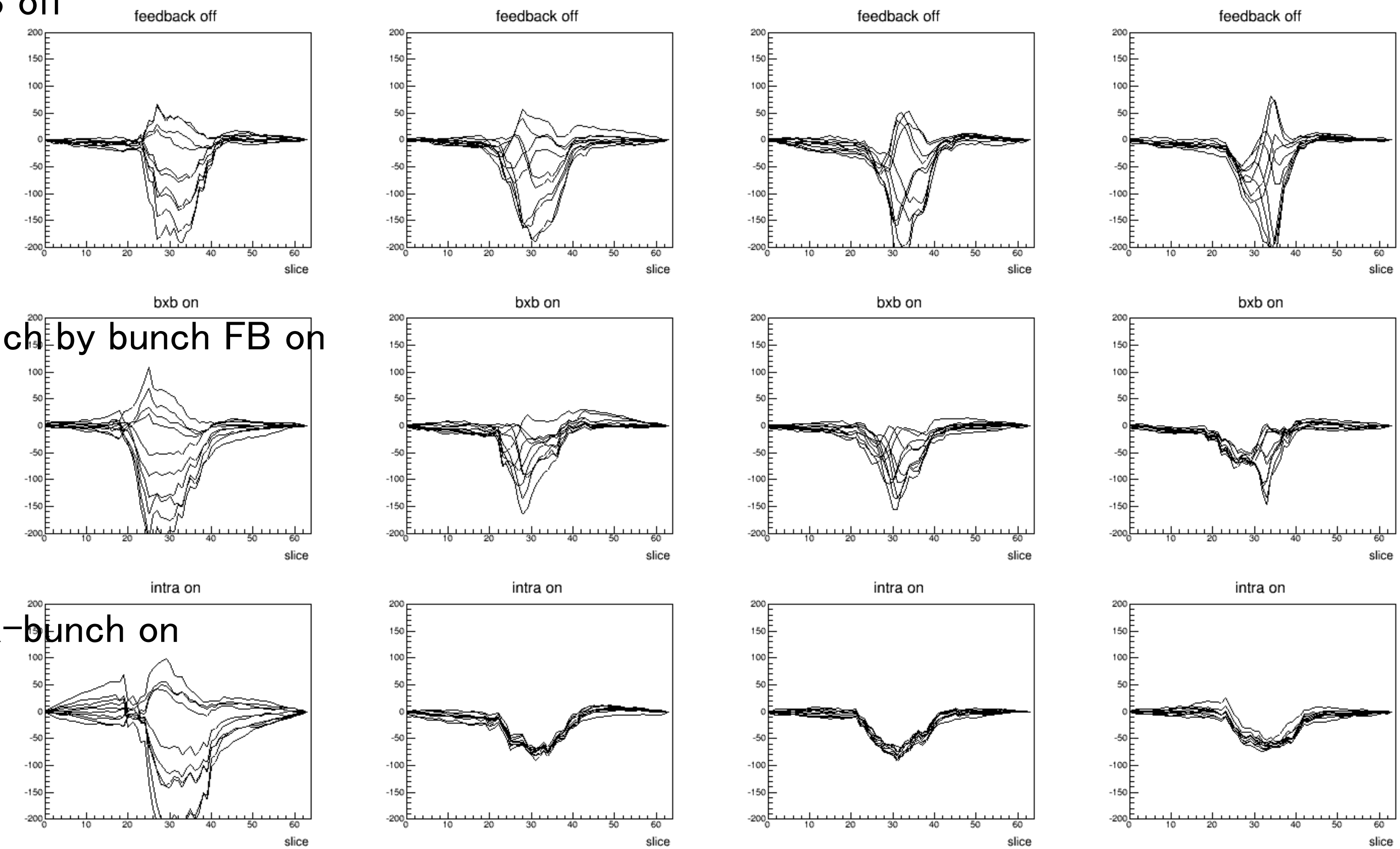
Delta signal motion

Signals are superimposed 10 times every 5turns

FB off

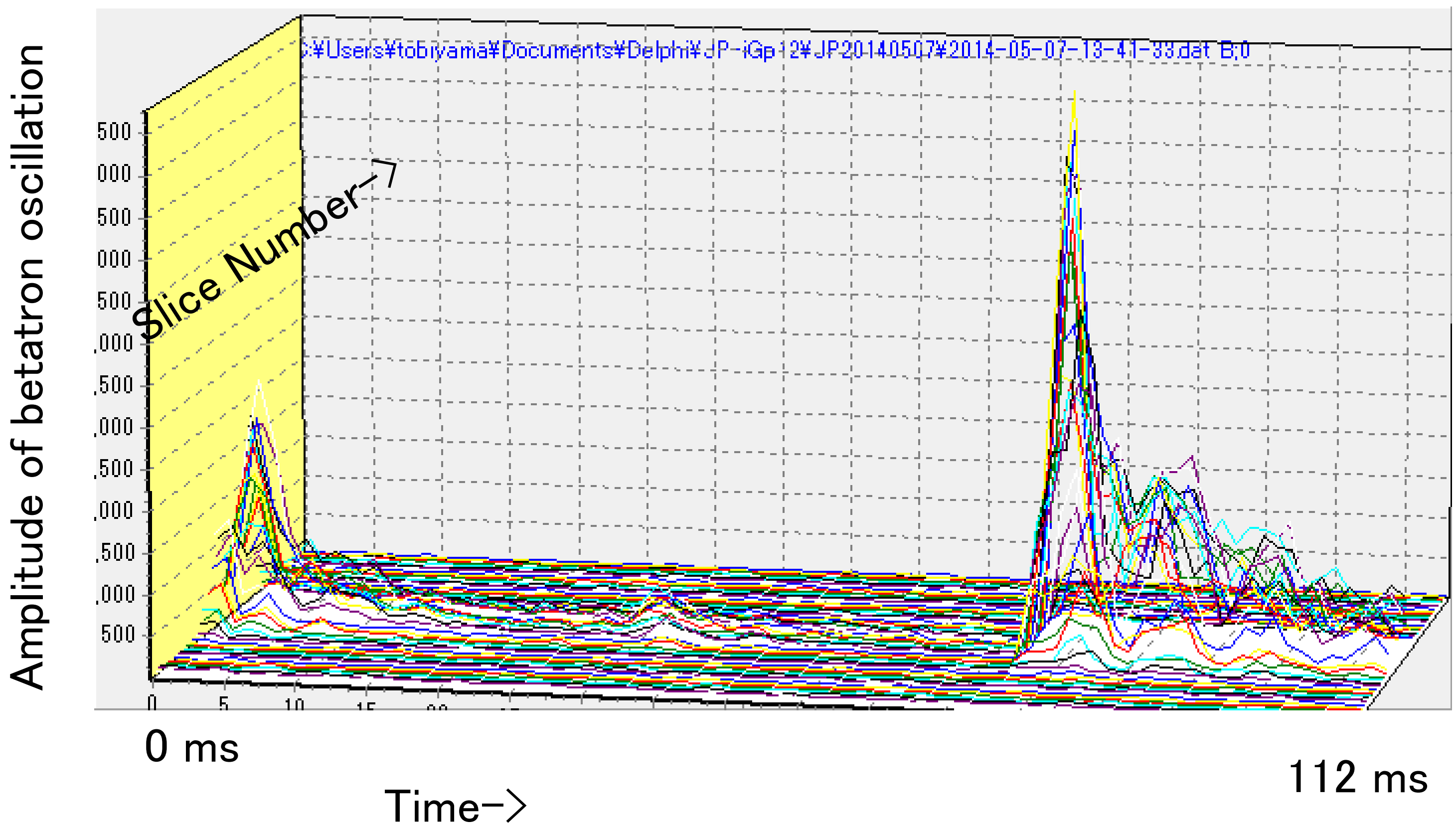
bunch by bunch FB on

intra-bunch on

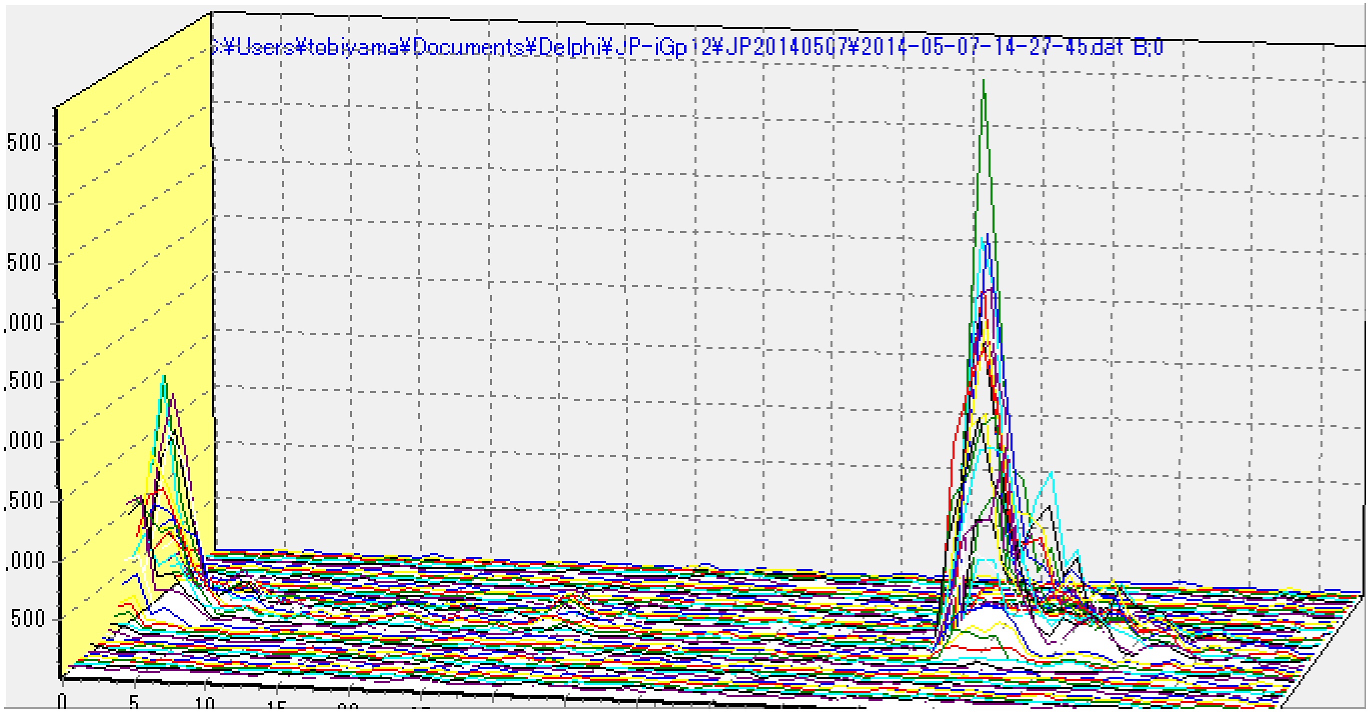


15200th turn | 15400th turn | 15600th turn | 15800th turn

w/o FB (Amplitude of β-freq. comp)



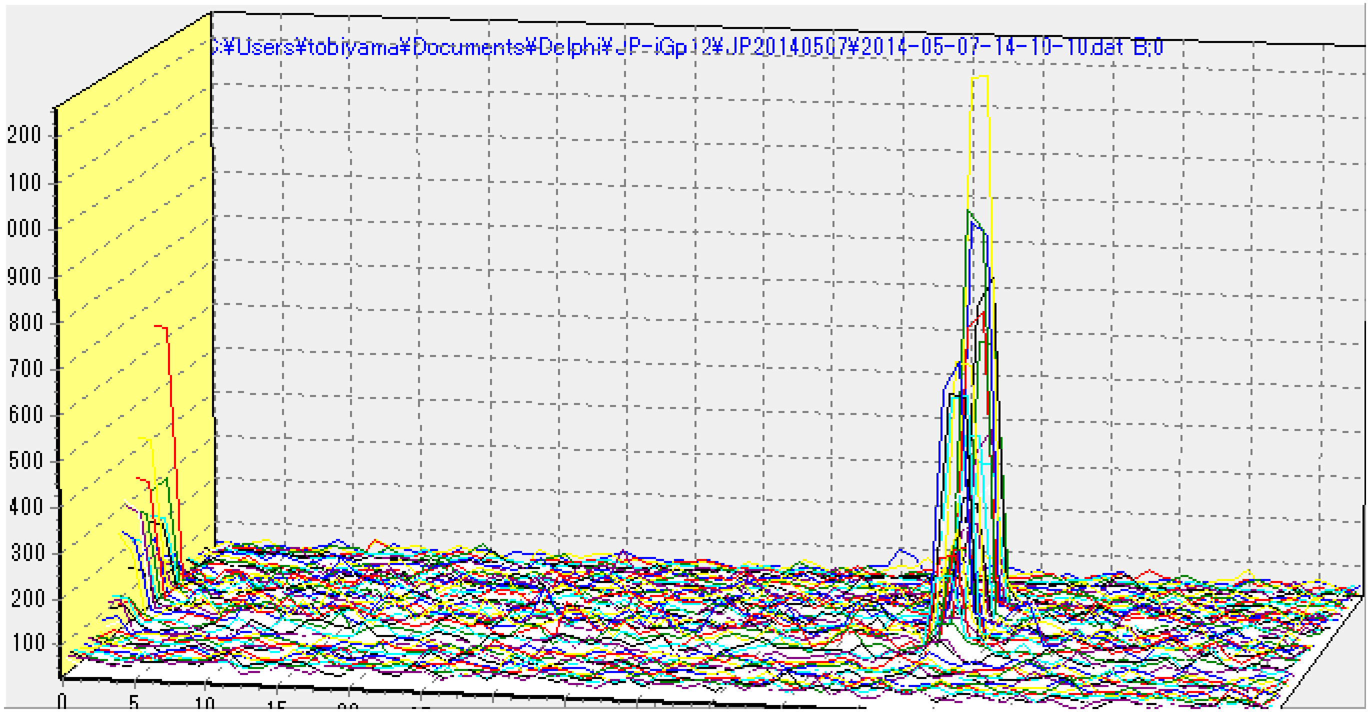
BxB FB ON



0 ms

112 ms

Intra-bunch FB (Shift gain=5) ON

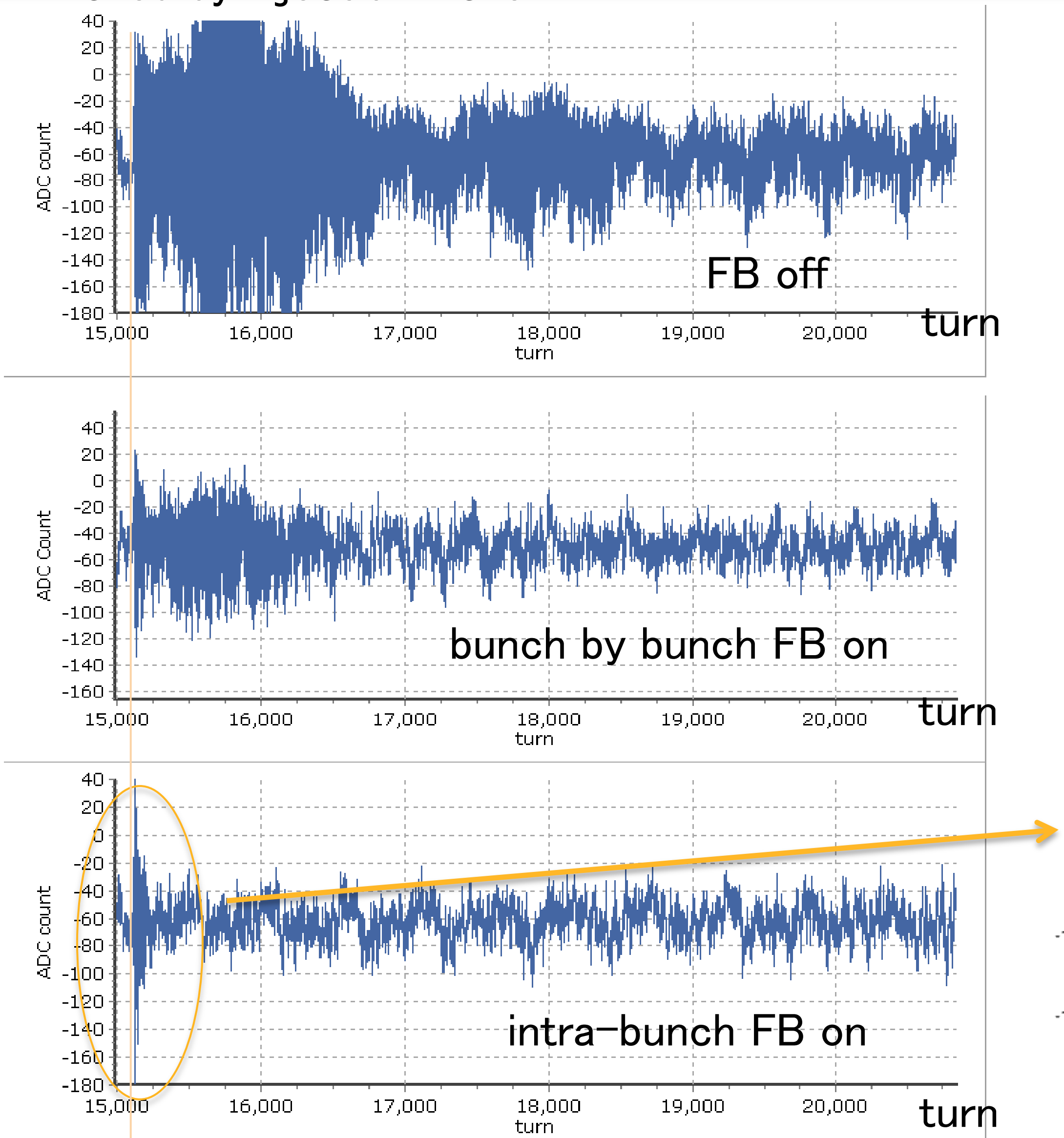


0 ms

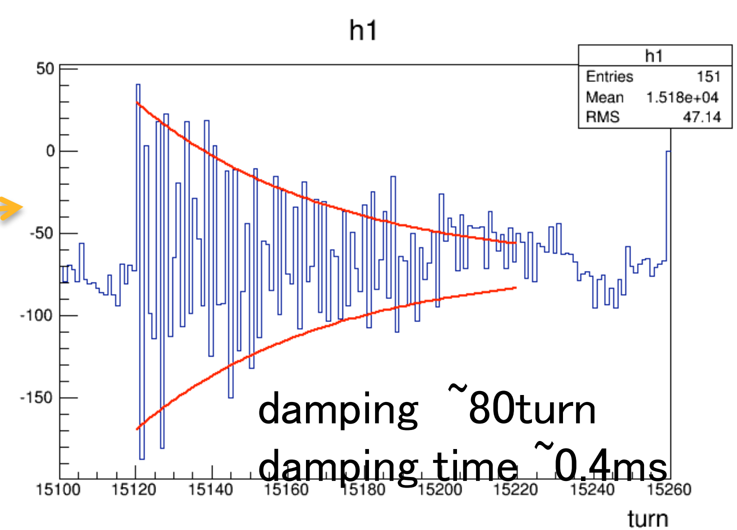
112 ms

Reduction of Oscillation Amplitude

Kicked by injection kicker



- We tested the supression of single kick by injection kicker mismatch.
- Intra- bunch FB suppresses oscillation amplitude effectively.
- Damping time was about 80 turns.

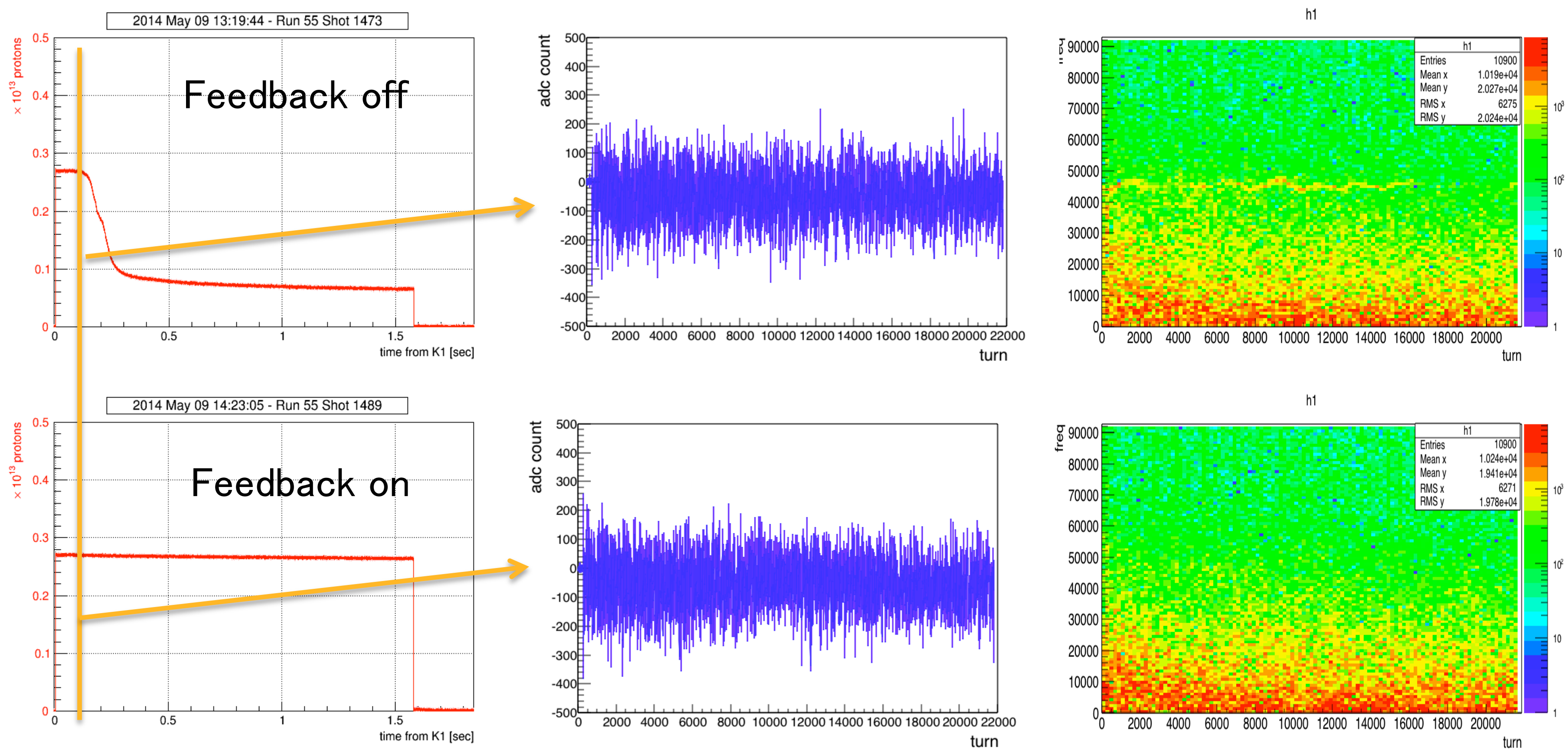


Suppression of vertical instability

Intensity

Amplitude of vertical oscillation

Spectgram

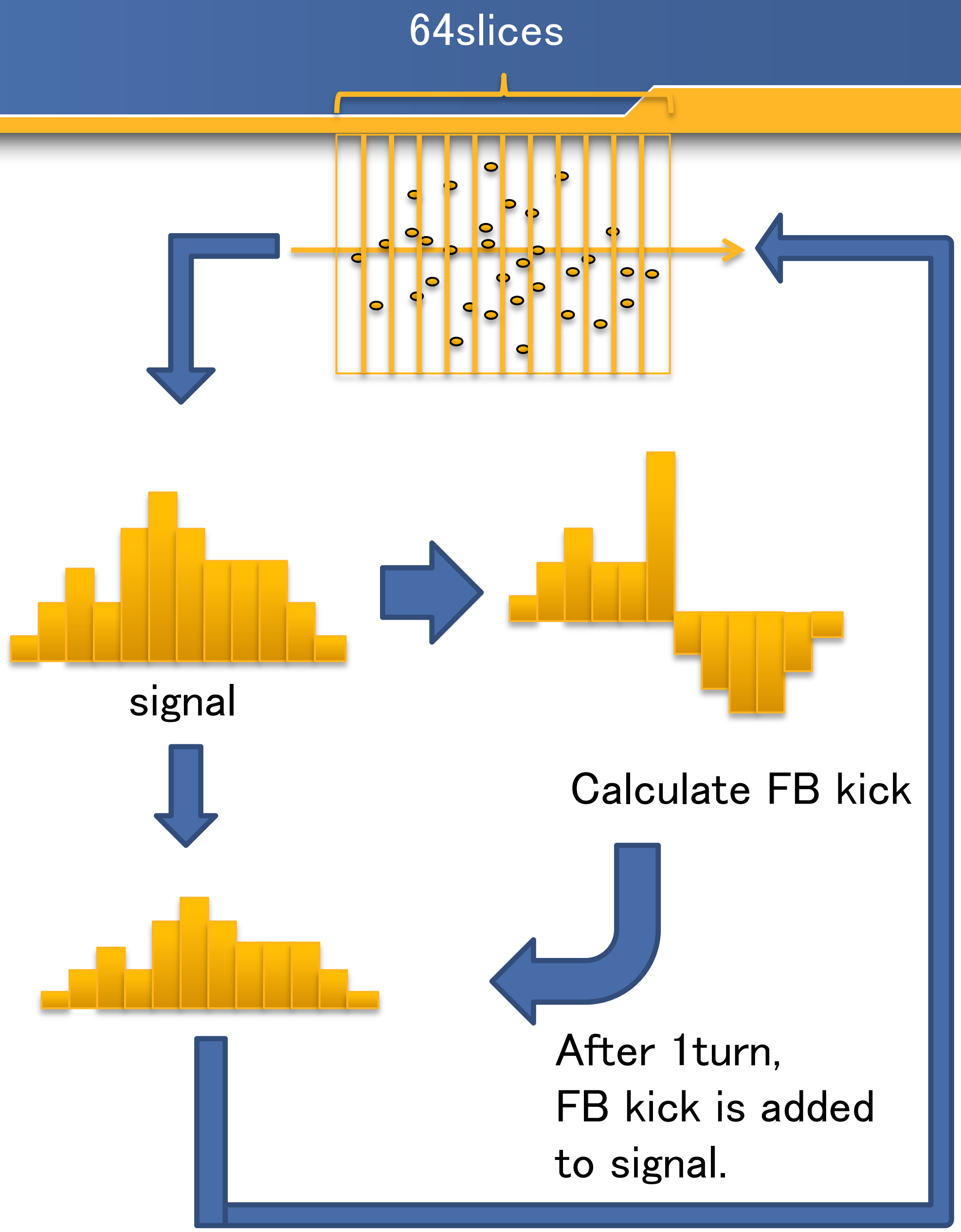


- We find intra-bunch feedback system is quite effective to suppress internal motion and to reduce beam loss.
- This system has been used during user operation now to reduce beam loss at injection.

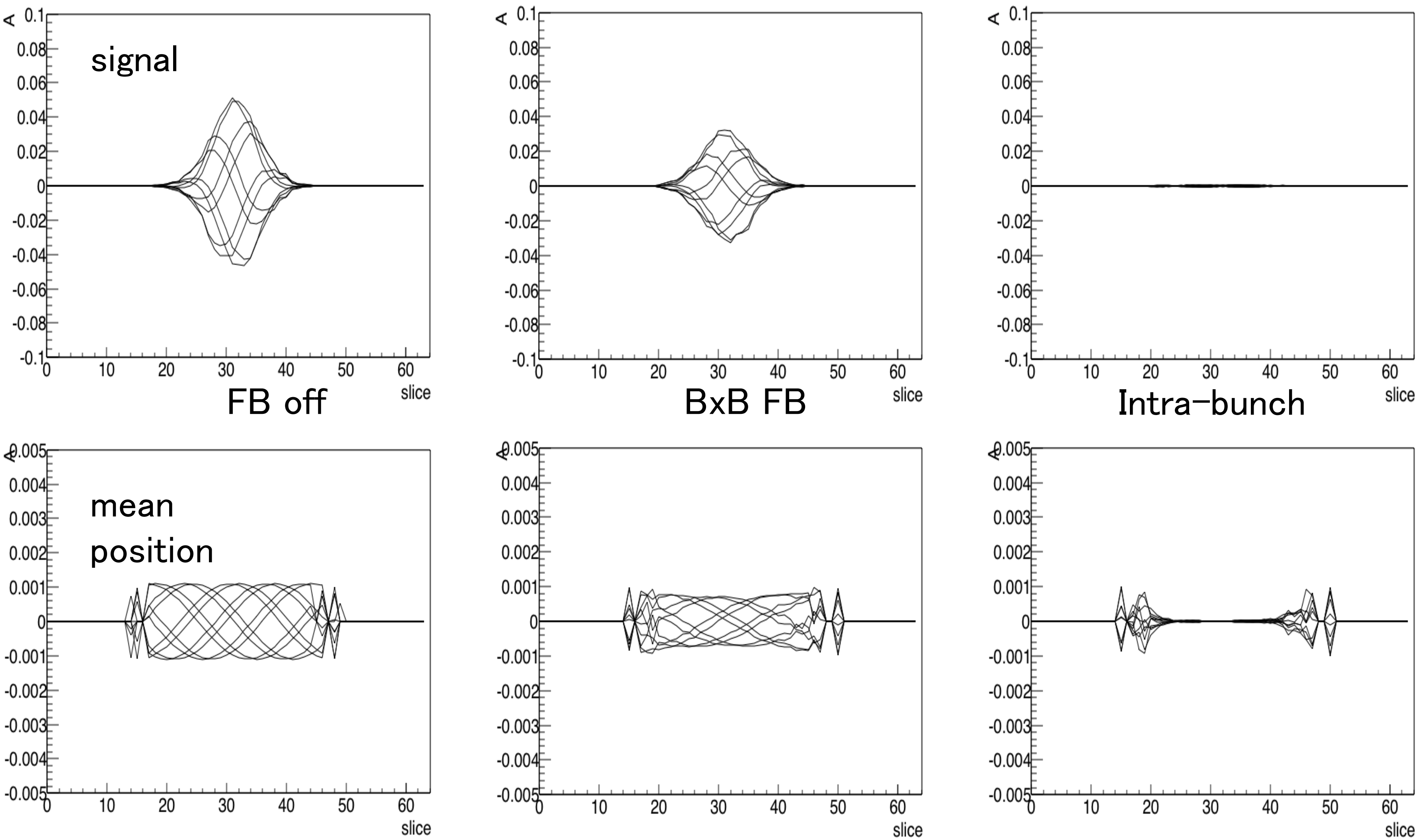
- We have tried to evaluate this system by comparison with macro particle simulations.
- In this time, only horizontal oscillations are taken into account.

Simulation Methods

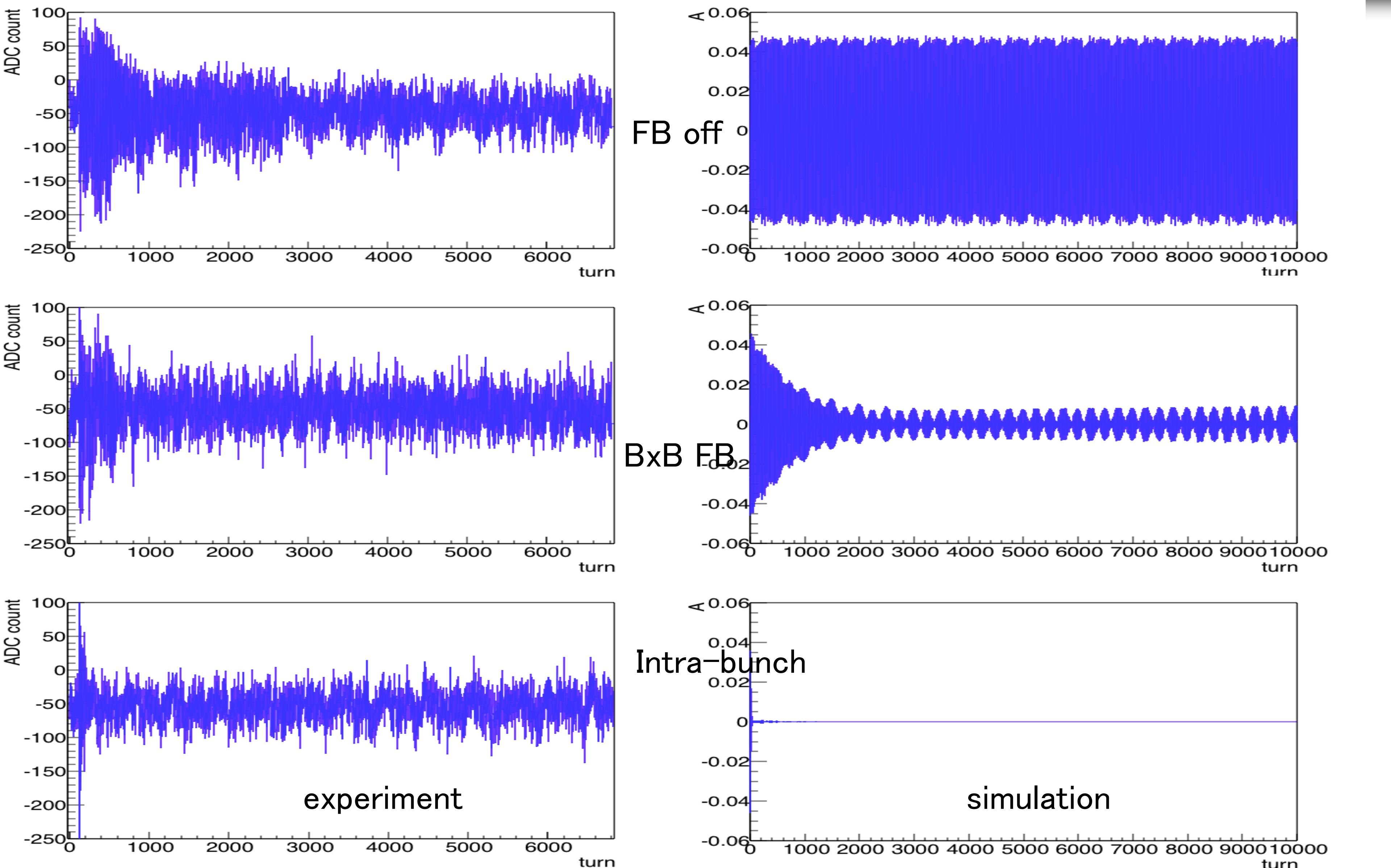
- **6400 macro particles are used.**
- **Each RF buckets are divided into 64 slices.**
- **No wake field.**
  - single bunch (Wake is not so effective in this beam test.)
- **No non-linear field.**
- **Space charge is not taken into account.**



Internal bunch motion and mean position

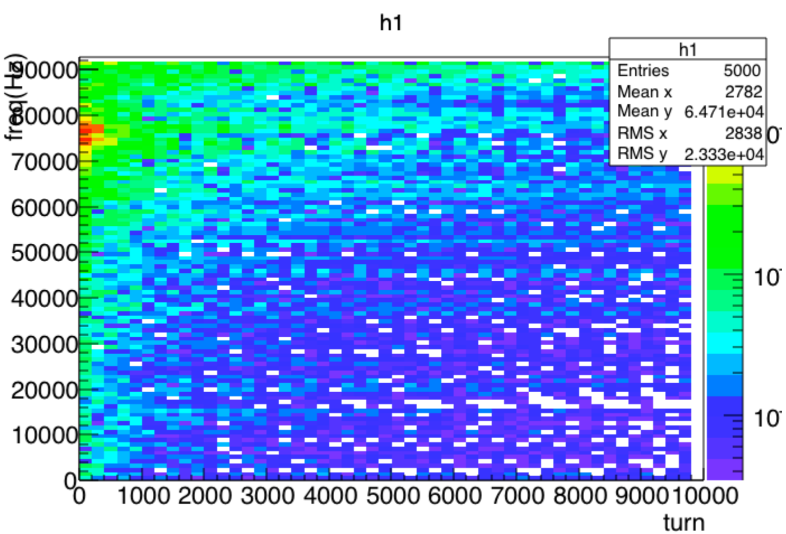


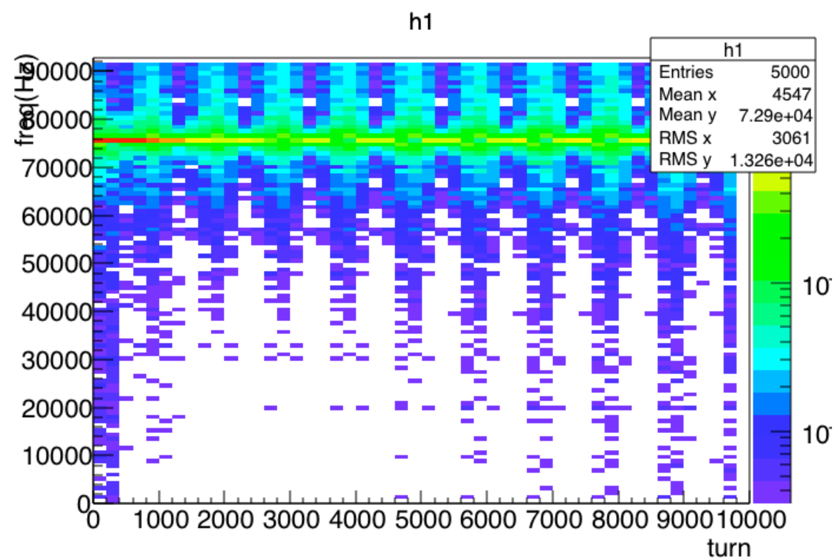
Damping behavior



Maximum gain/Damping time

- **Unstable with too large feedback gain**
  - Very rough estimate..
  - Intra-bunch FB(8tap) ~2.0e-4 damping time ~40turn
  - BxB FB (4tap) ~3.125e-6 damping time ~2000turn
- **Larger feedback gain (might be) available with Intra-bunch FB.**





Summary

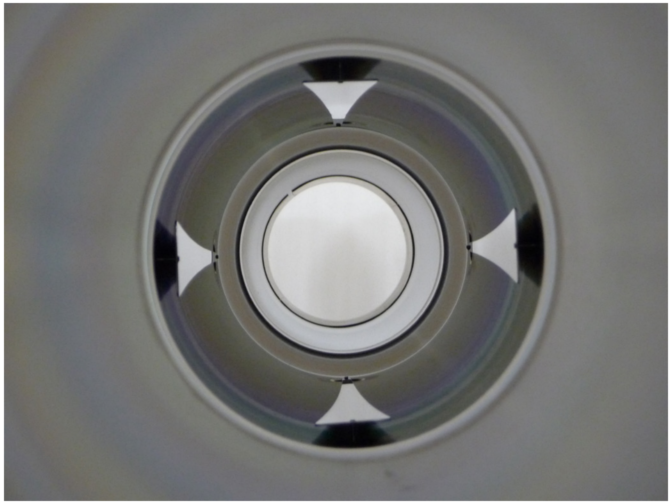
- **Constructed and tested intra-bunch feedback system at J-PARC MR.**
  - Shown excellent performance.
  - Necessary for stable high beam power operation (both X and Y)
    - Insufficient tuning of the system (due to very tight MD time)
    - Need detailed tuning (FIR filter phase, Delay, etc.)
  - Analysis of instability data, especially during acceleration.
- **Tried very simple simulation**
  - Larger stable feedback gain will be achievable by the intra-bunch feedback system.
  - Additional effect (space charge, wake fields (mainly coming from resistive wall), nonlinear fields..) will be implemented.
  - Multi-bunch (coupled bunch) effects.

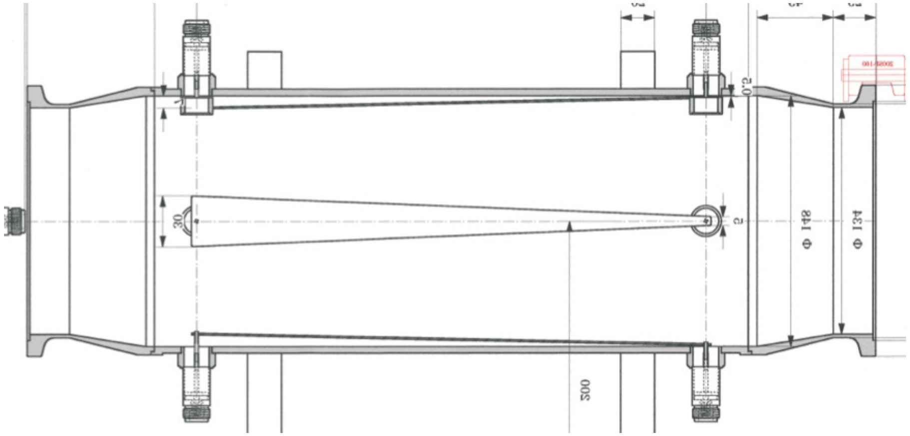
Backups

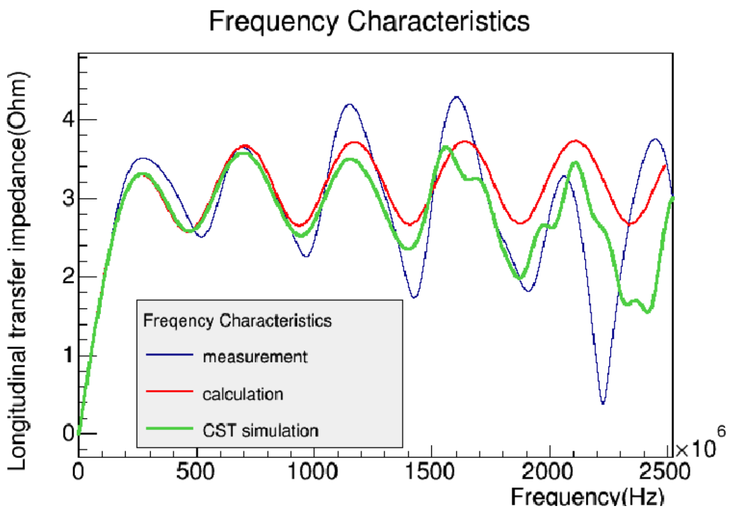
BPM (Beam Position Monitor)

- Linnecar's design in SPS.

It has exponentially tapered electrodes, which allow wideband frequency sensitivities compared to normal BPM.

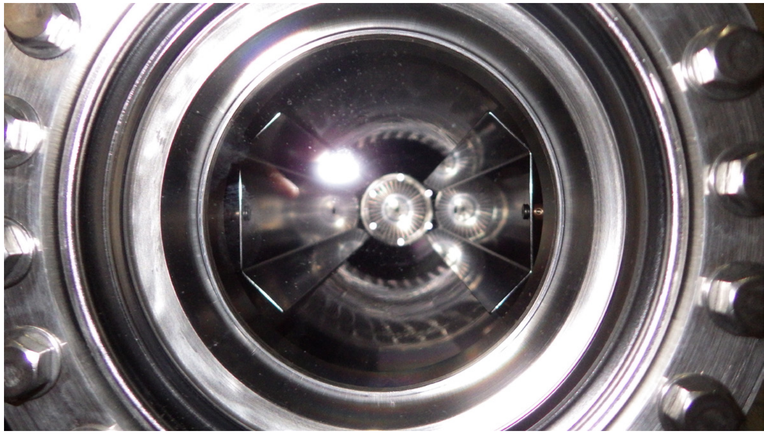


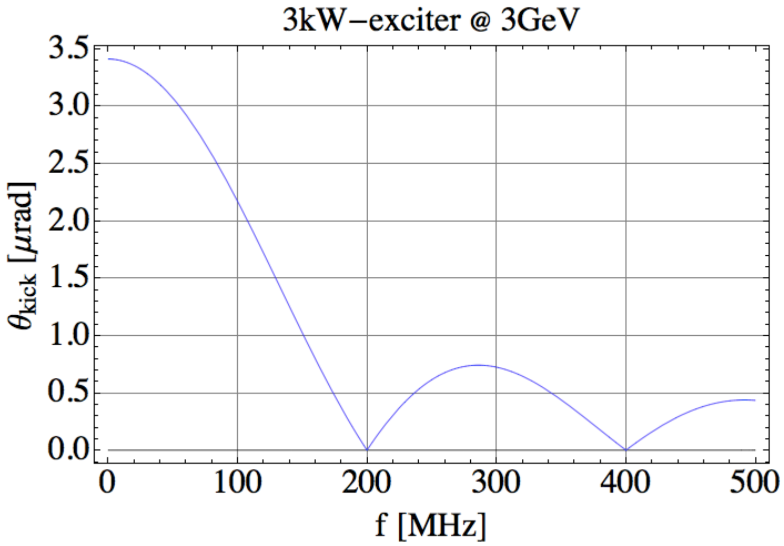


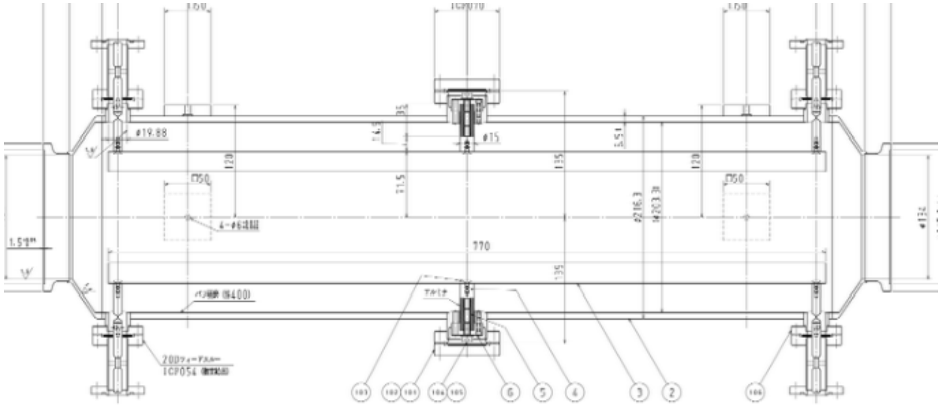


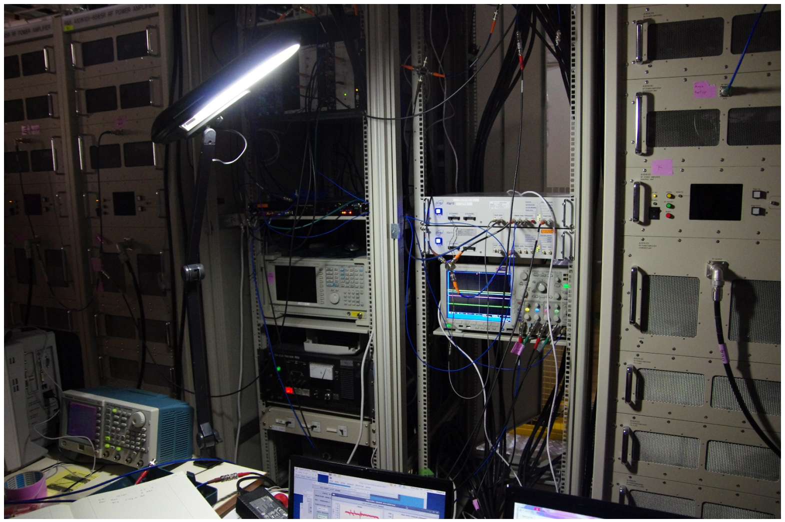
kickers and power amplifiers

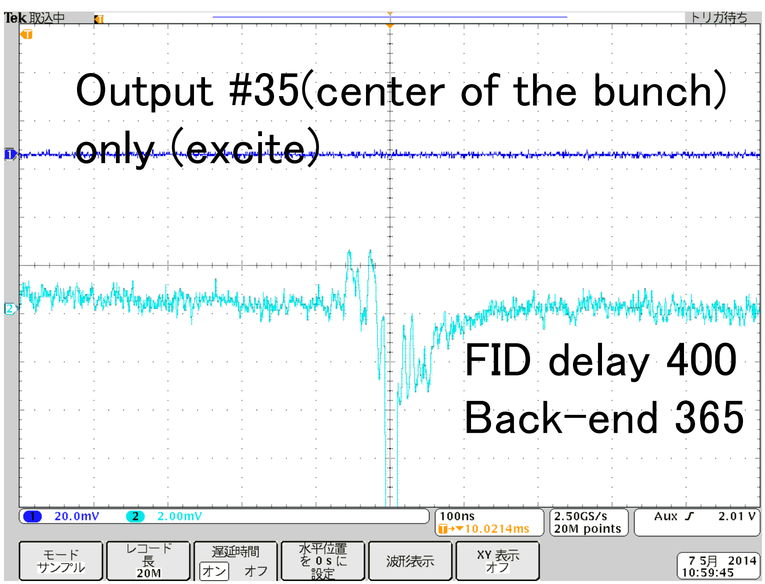
- New stripline kicker (L=0.77m).
- Diamond-like Carbon coating for reduction of multipactoring when used for slow extraction (CW operation).
- Kick angle is 3.5 μrad at 3GeV with two 3kW power amps.
- 3kW power amplifiers with bandwidth of 100kHz-100MHz.



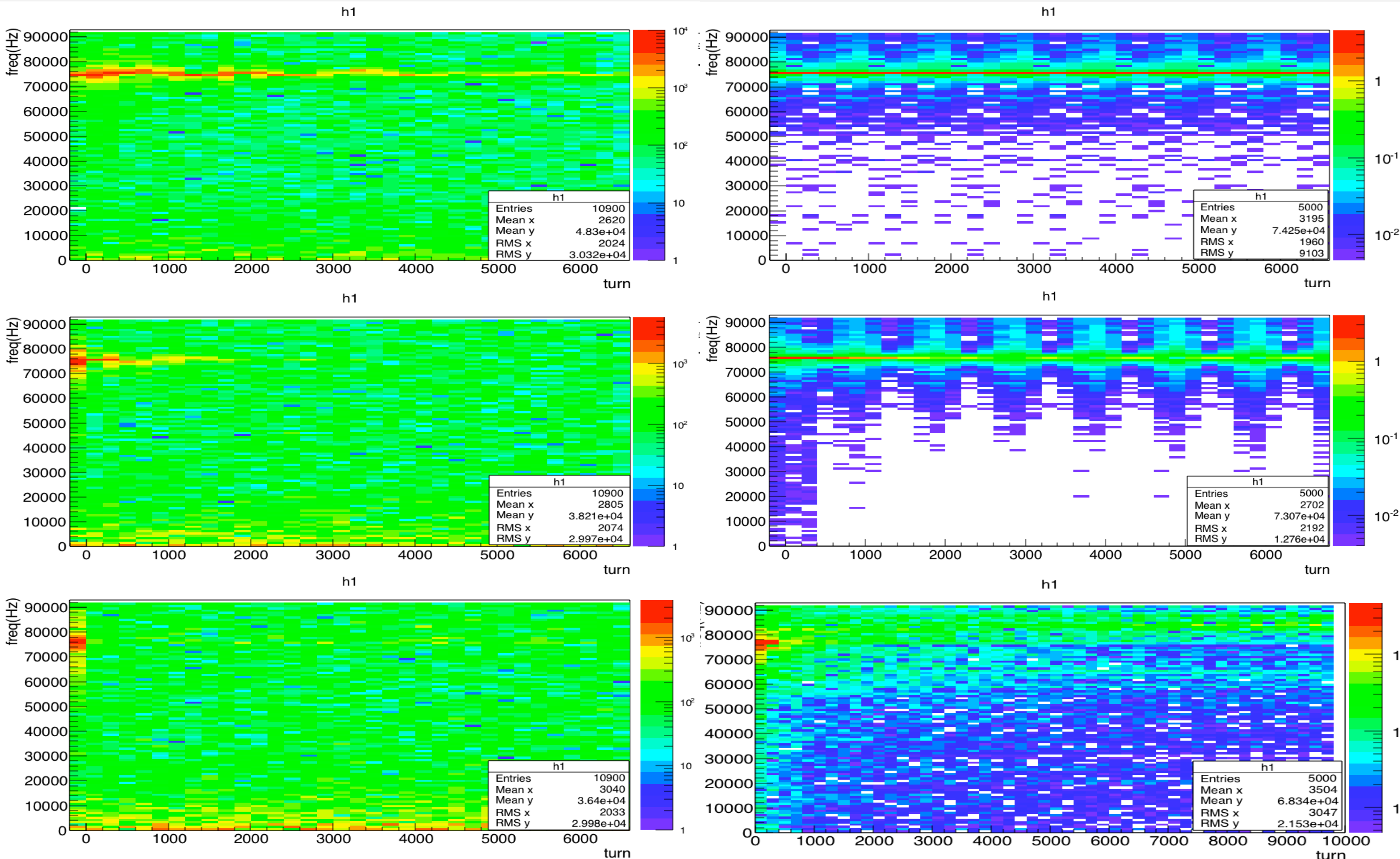


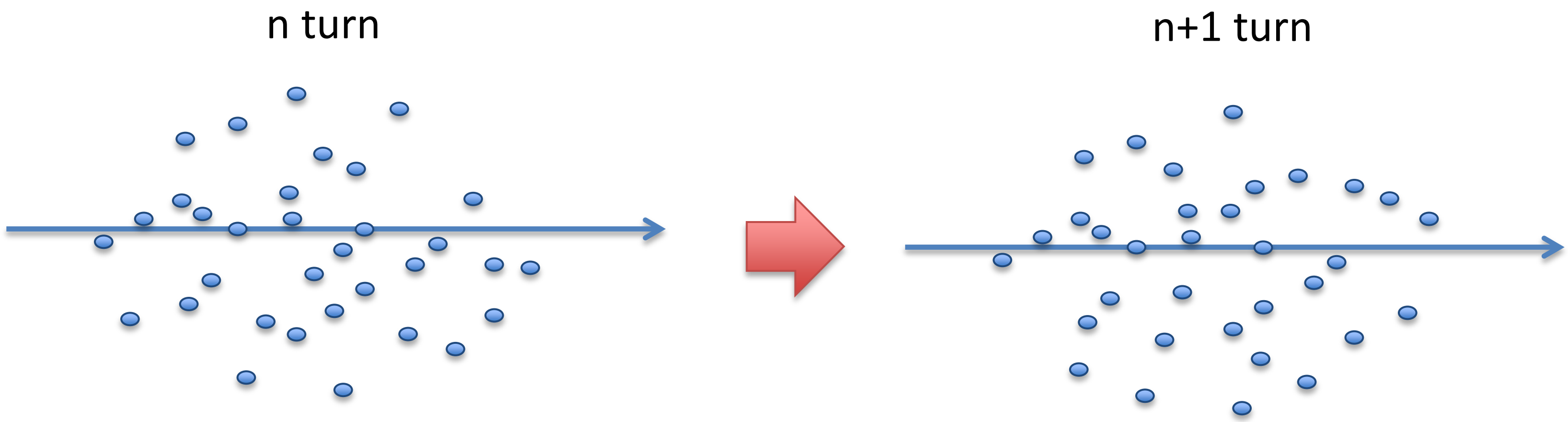





Tek 取込中
トリガ待ち
Output #35(center of the bunch) only (excite)
FID delay 400
Back-end 365
1 20.0mV
2 2.00mV
100ns
10.0214ms
2.50GS/s
20M points
Aux 2.01 V
モード サンプル
レコード長 20M
遅延時間 オン オフ
水平位置を0sに設定
波形表示
XY 表示 オフ
7 5月 2014
10:59:45

修正版


h1
freq(Hz)
turn
Entries 10900
Mean x 2620
Mean y 4.83e+04
RMS x 2024
RMS y 3.032e+04
h1
freq(Hz)
turn
Entries 5000
Mean x 3195
Mean y 7.425e+04
RMS x 1960
RMS y 9103
h1
freq(Hz)
turn
Entries 10900
Mean x 2805
Mean y 3.821e+04
RMS x 2074
RMS y 2.997e+04
h1
freq(Hz)
turn
Entries 5000
Mean x 2702
Mean y 7.307e+04
RMS x 2192
RMS y 1.276e+04
h1
freq(Hz)
turn
Entries 10900
Mean x 3040
Mean y 3.64e+04
RMS x 2033
RMS y 2.998e+04
h1
turn
Entries 5000
Mean x 3504
Mean y 6.834e+04
RMS x 3047
RMS y 2.153e+04



各粒子に対して以下の運動方程式で1turn後を計算

縦方向(シンプレクティックオイラー法)

$$\tau_{n+1} = \tau_n - \frac{\eta}{\beta c}\Delta s \delta_n \quad \delta_{n+1} = \delta_n + \frac{\beta c}{\eta}\left(\frac{\nu_{s0}}{R}\right)^2 \Delta s \tau_{n+1}$$

横方向

$$x_{n+1} = (\cos\mu + \alpha\sin\mu)x_n + \beta\sin\mu p_n$$

$$p_{n+1} = -\gamma\sin\mu x_n + (\cos\mu - \alpha\sin\mu)p_n$$

$$\mu = 2\pi(\nu_x + \xi\delta_n)$$

Filters

- 8tap FIR filters are used to derive betatron oscillation.
- Filter coefficients are given below.

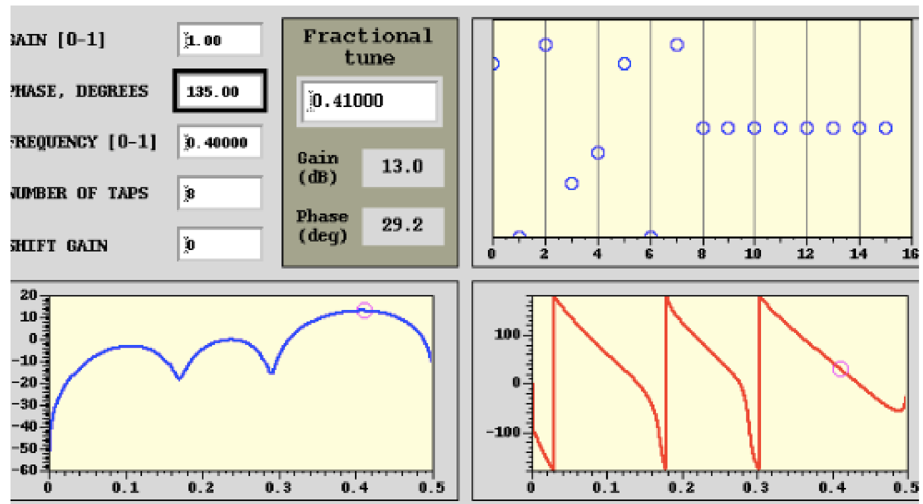
$$b[n] = \sin((n-1)\omega T_s + \Delta\phi) - \Delta$$

$$\Delta = \frac{1}{N_{tap}} \sum_{n=0}^{N_{tap-1}} \sin(n\omega T_s + \Delta\phi)$$

- BxB feedback system
  - Only the peak value of bunch signals are used.
- Intra-bunch feedback system
  - Each slice is filtered.

$$\omega = 0.4, \Delta\phi = -30$$

$$\omega = 0.4, \Delta\phi = 135$$



Filter characteristics of intra-bunch FB

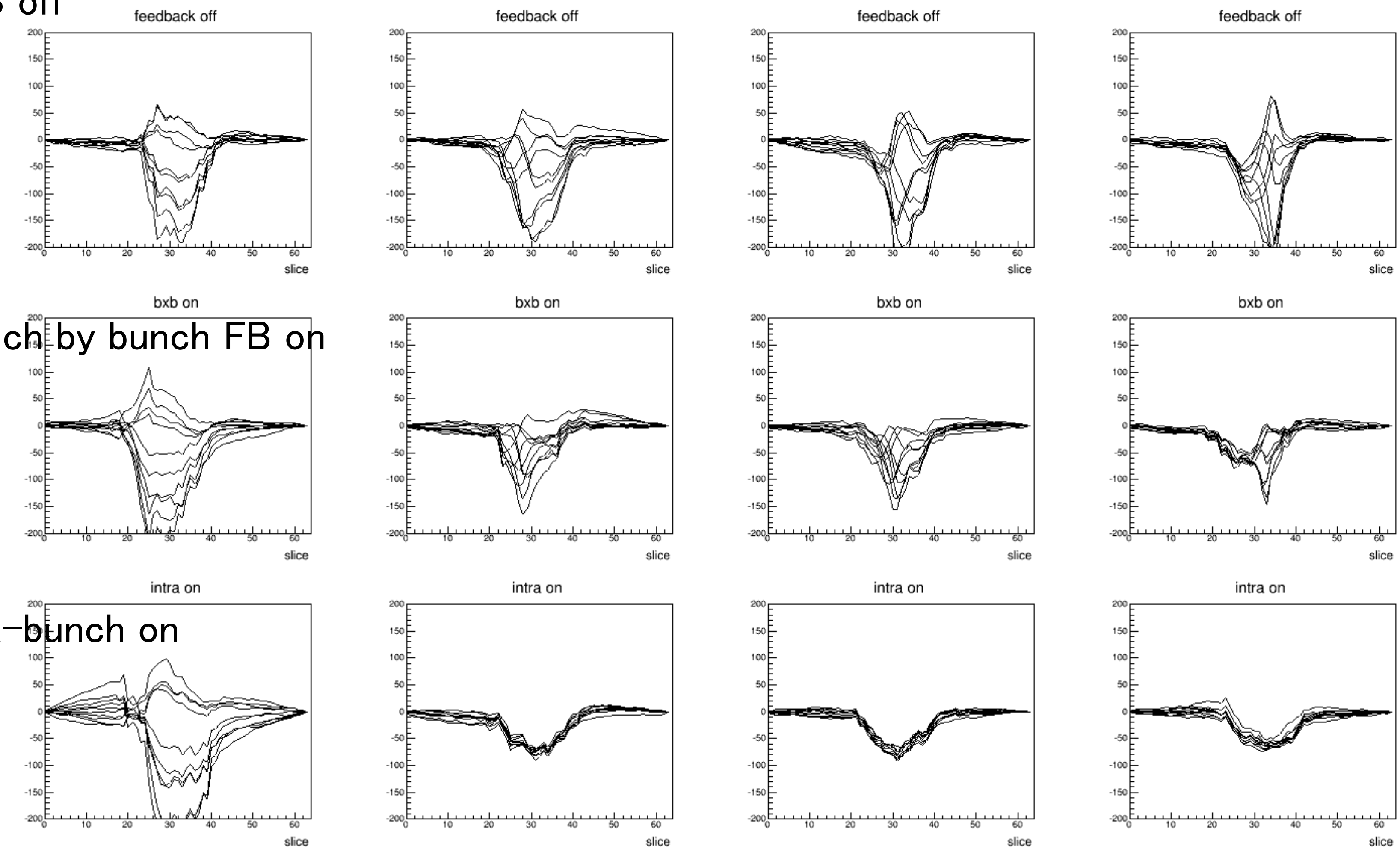
Delta signal motion

Signals are superimposed
10 times every 5turns

FB off

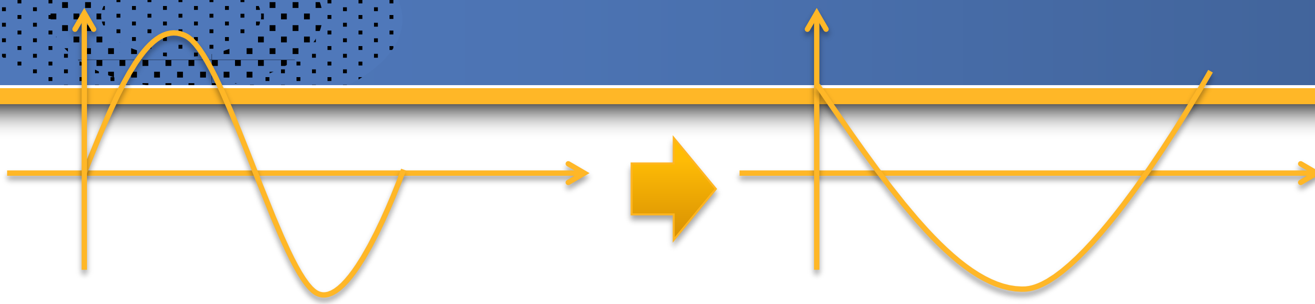
bunch by bunch FB on

intra-bunch on



15200th turn | 15400th turn | 15600th turn | 15800th turn

IBFBの場合

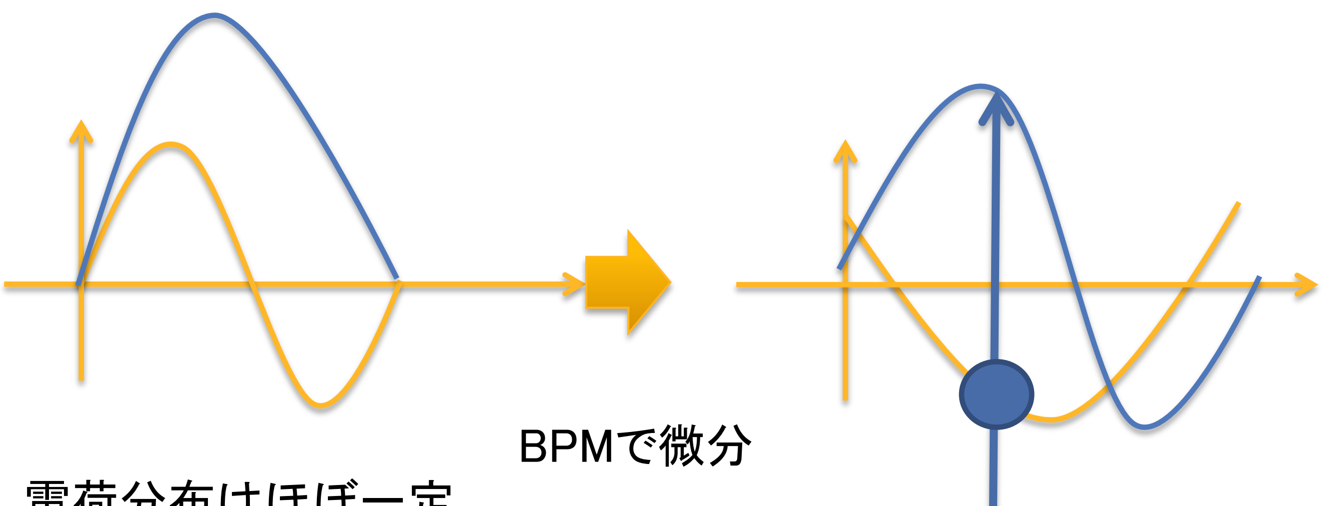


モジュール内で積分しているので、そのまま利用

信号=dipole電流

BPMで微分

BxBの場合

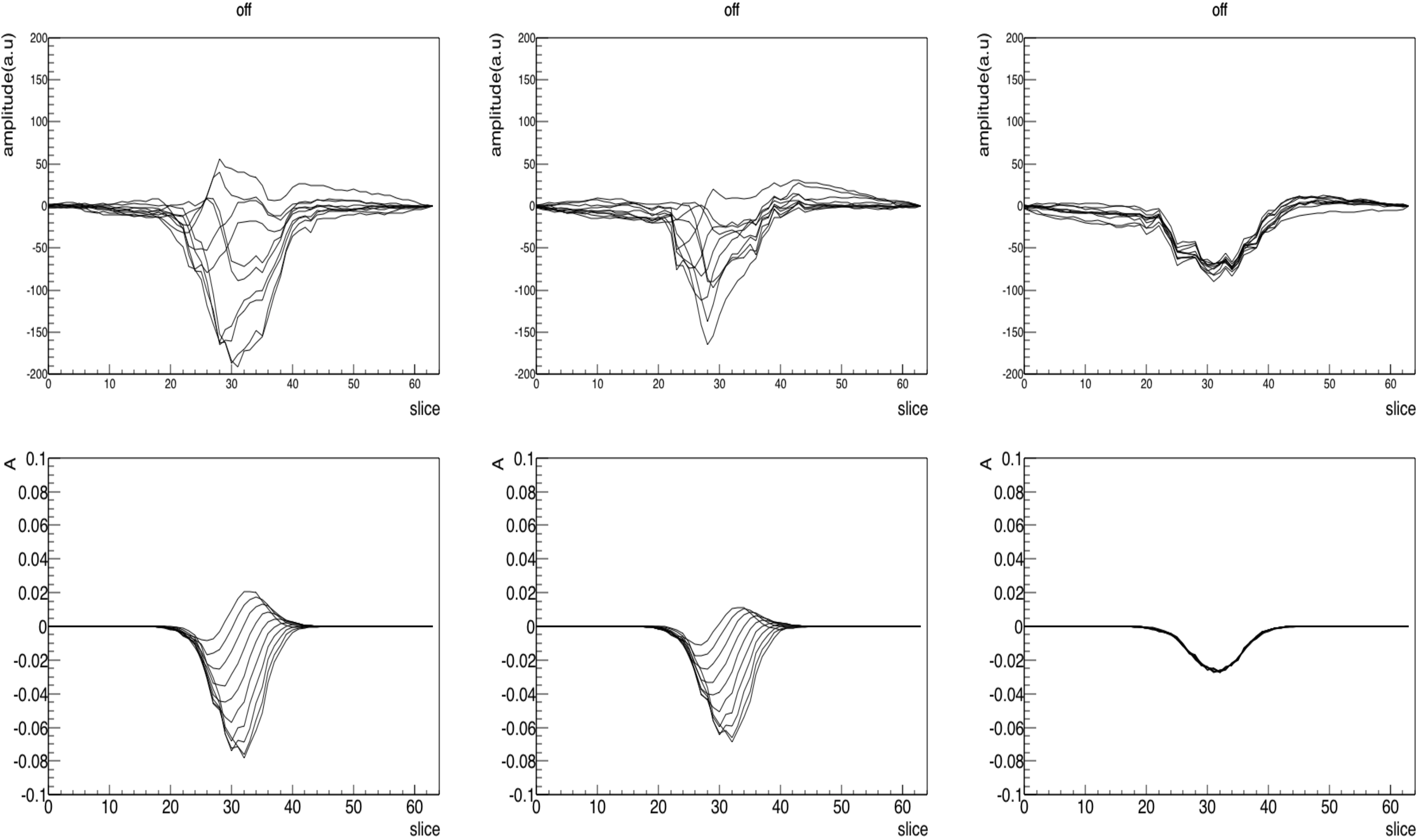


微分した信号の電流のピーク値のところで信号をサンプリング

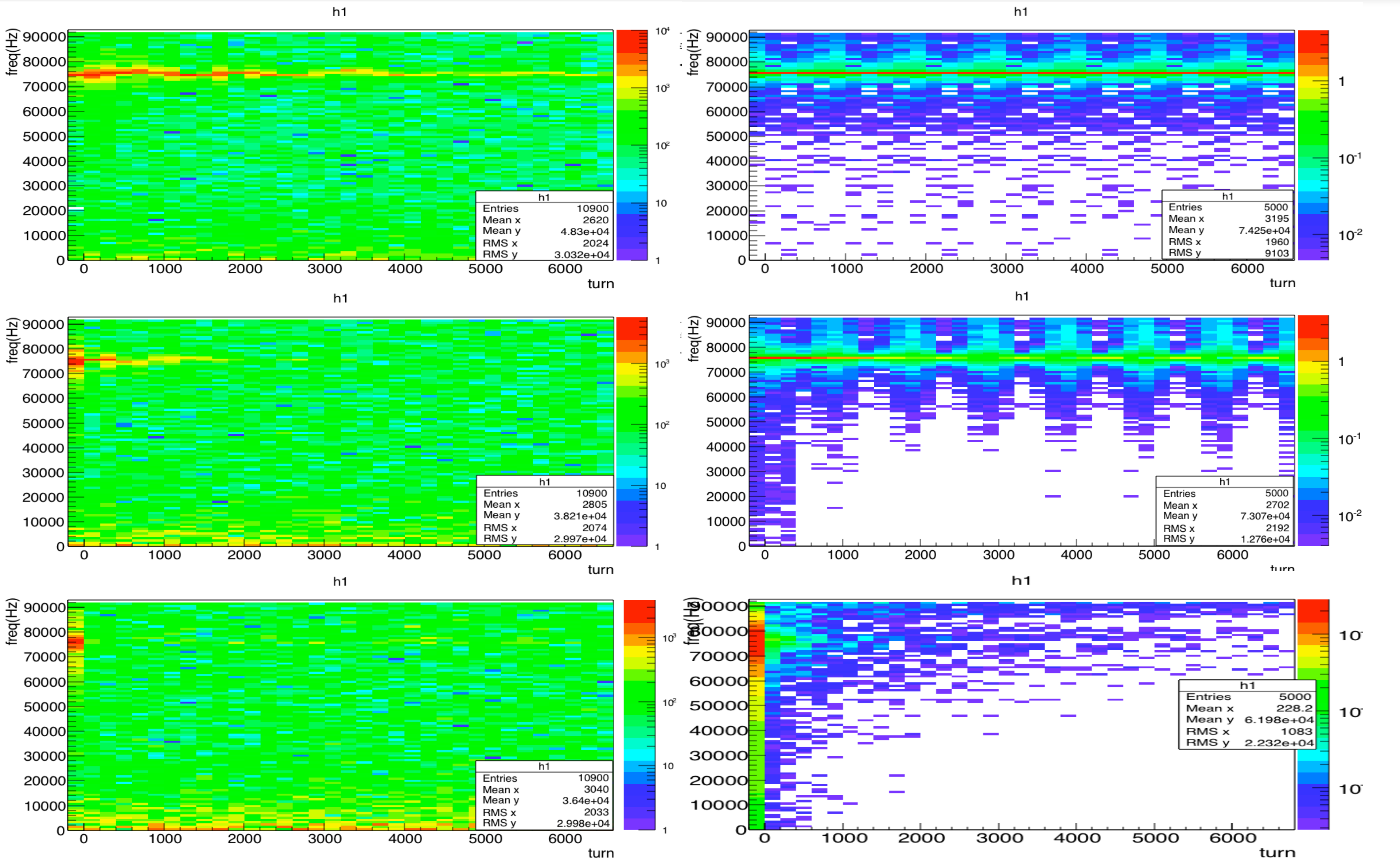
電荷分布はほぼ一定

BPMで微分

微分の後 IIR filterをかけている
->signalと大きさ大体同じになるよう規格化

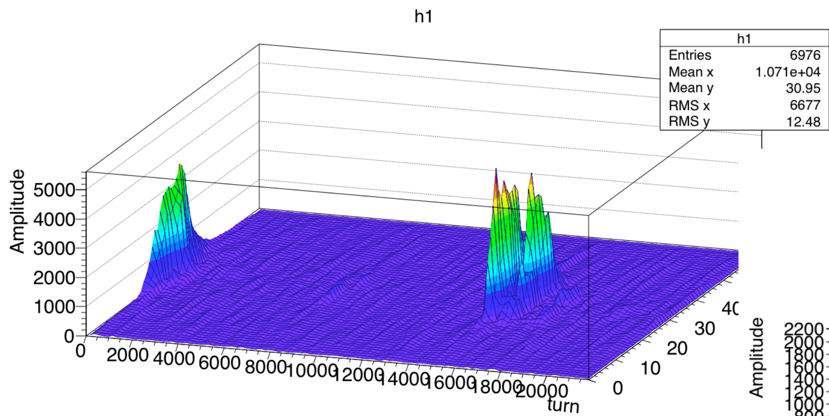

off
off
off
amplitude(a.u)
slice
A
slice

Spectgrams

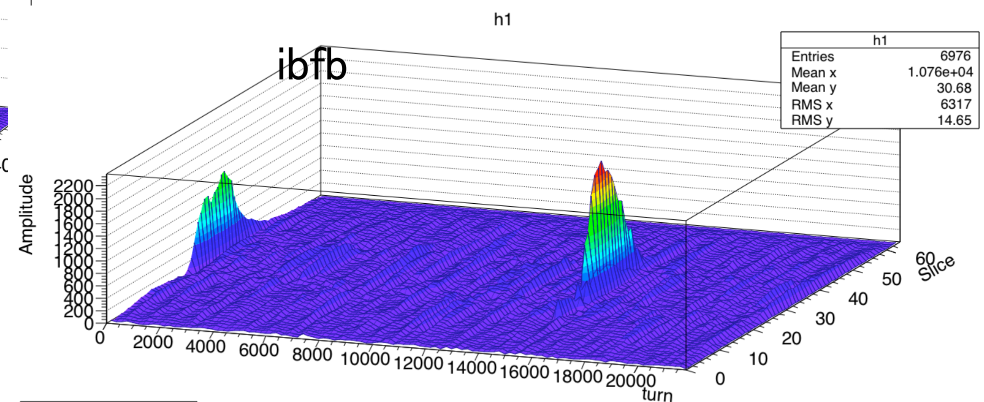

h1
freq(Hz)
turn
h1
Entries 10900
Mean x 2620
Mean y 4.83e+04
RMS x 2024
RMS y 3.032e+04
h1
Entries 5000
Mean x 3195
Mean y 7.425e+04
RMS x 1960
RMS y 9103
h1
Entries 10900
Mean x 2805
Mean y 3.821e+04
RMS x 2074
RMS y 2.997e+04
h1
Entries 5000
Mean x 2702
Mean y 7.307e+04
RMS x 2192
RMS y 1.276e+04
h1
Entries 10900
Mean x 3040
Mean y 3.64e+04
RMS x 2033
RMS y 2.998e+04
h1
Entries 5000
Mean x 228.2
Mean y 6.198e+04
RMS x 1083
RMS y 2.232e+04

waterfall plot(もどき) 実験

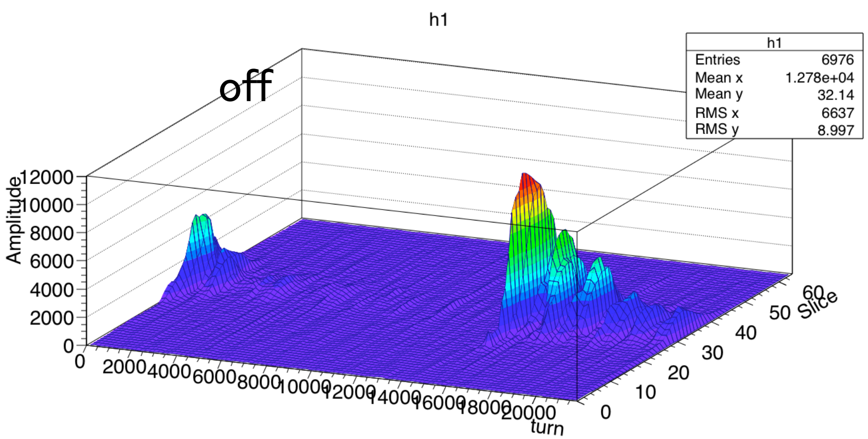
bxb



ibfb

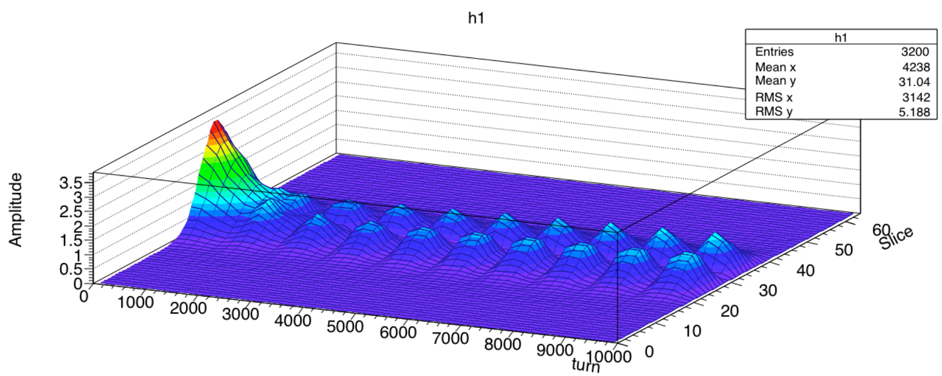


off

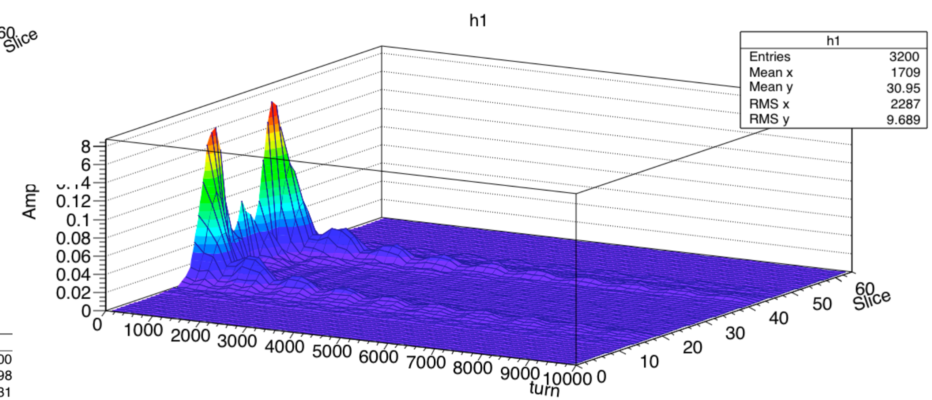


waterfall plot(もどき) sim

bxb



ibfb



off