Beam Instability Issue and Transverse Feedback System in the MR of J-PARC

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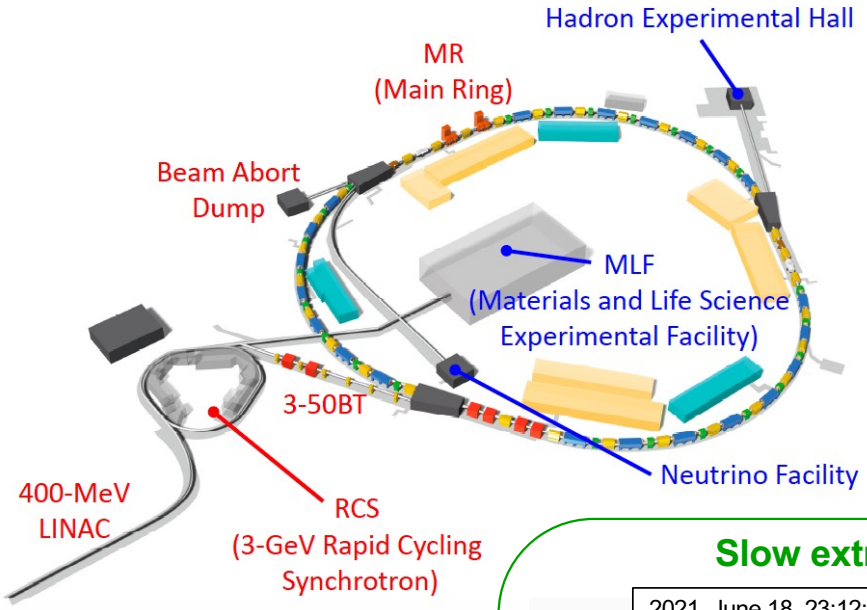
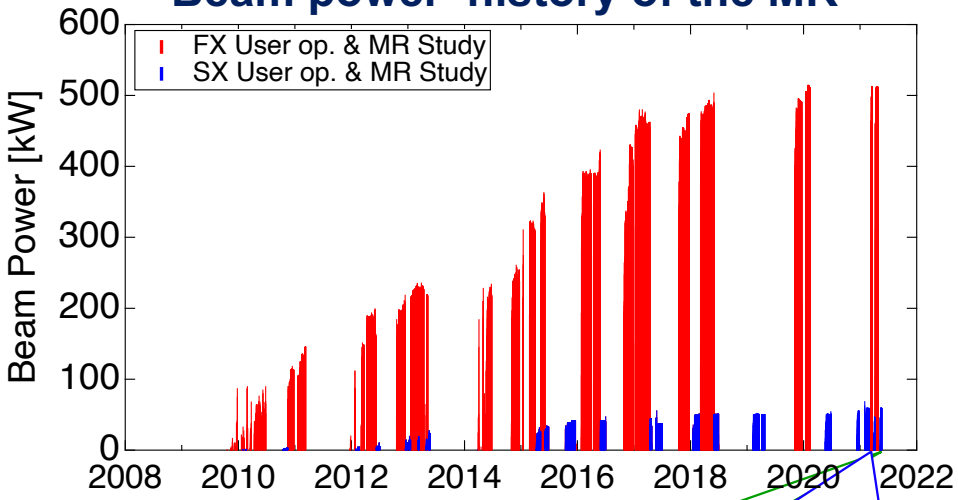
Special Thanks

Dmitry Teytelman

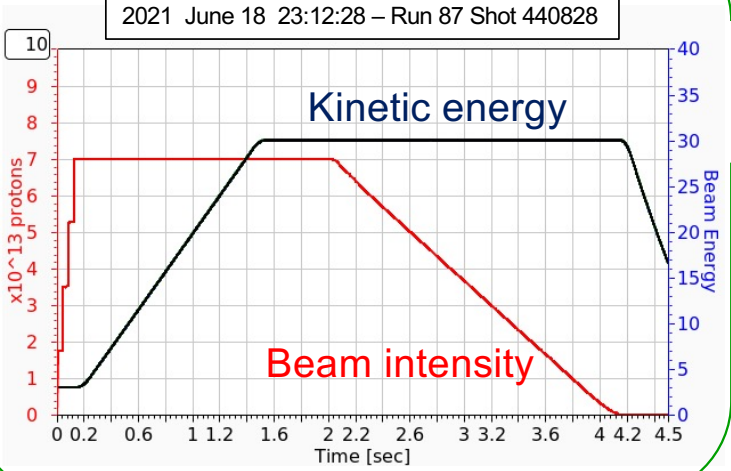
Schematic layout of J-PARC accelerators and experimental facilities



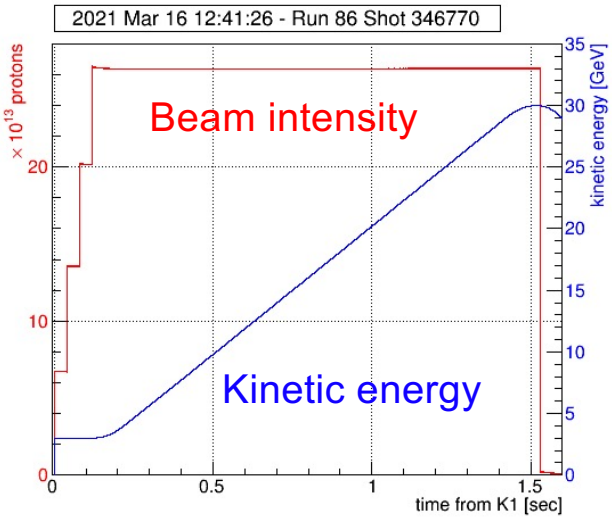
Beam power history of the MR



Slow extraction (SX)



Fast extraction (FX)



Present observations in the MR

In the SX mode

Recent stable routine operations ~ 64 kW (~7E+13 protons/pulse, 8 bunches)

"Bunch-by-bunch (Hor./Ver.) feed back system" is utilized

ν_x ~ 22.30, ν_y ~ 21.75, ξ_x = -5, ξ_y= -7.1 (during debunching process)

Limiting factor to increase the SX beam power

debunching @ 30 GeV flat-top → longitudinal microwave instability

→ electron cloud buildup

→ transverse instability, vacuum pressure rise, beam loss

(to be confirmed that this is the electron cloud instability)

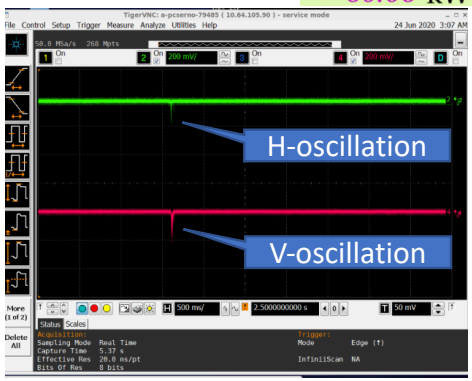
SX mode

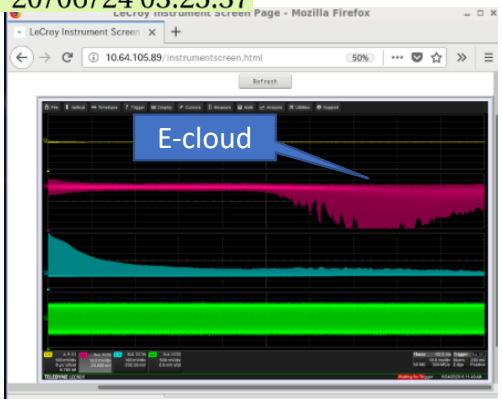
Beam Instability at debunch Timing

Currently Limiting SX beam intensity (large beam loss for SX)

Abort destination, 60kW debunch , RF offset 65deg

Shot *311512* at *20/06/24 03:24:49*
60.06 kW 20/06/24 03:25:37

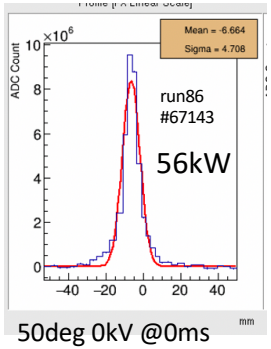


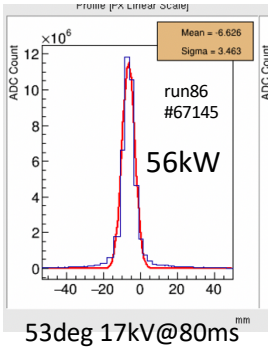


H, V beam size growth

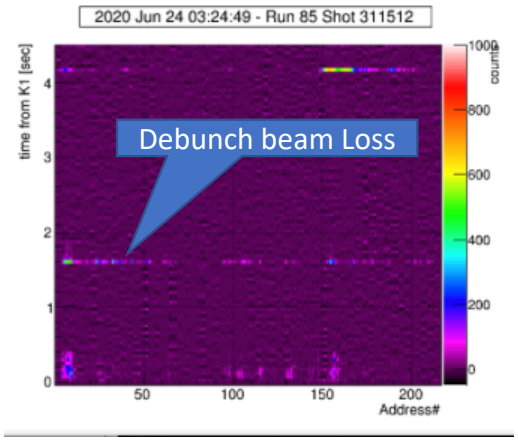
56kW

w/Insta. w/o Insta.

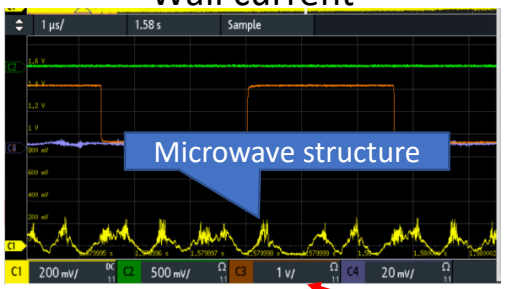




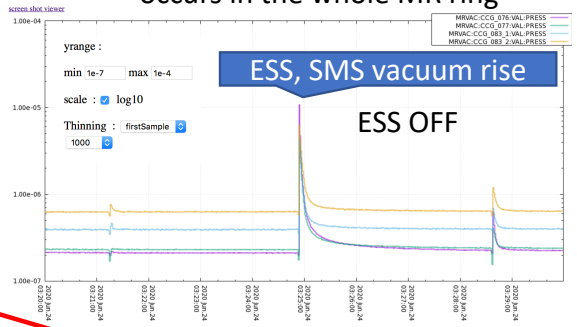
50deg 0kV @0ms 53deg 17kV@80ms



Wall current



occurs in the whole MR ring



The transverse instability (e-p) seems to be triggered by a longitudinal micro-structure in debunch

M. Tomizawa, ATAC2021

Present observations in the MR

In the FX mode

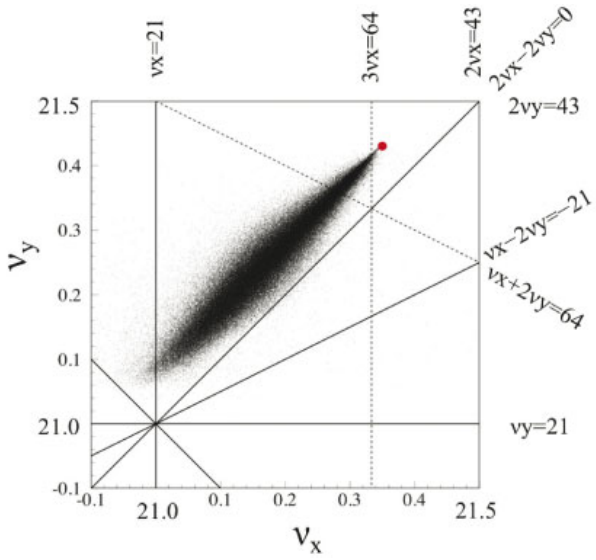
Recent stable routine operations ~ 500 kW (~2.6E+14 protons/pulse, 8 bunches)

Transverse (Hor./Ver.) intra-bunch feed back system is an essential ingredient

Another essential ingredient is hor. & ver. chromaticity,

$\nu_x \sim 21.34$, $\nu_y \sim 21.43$

$\xi_x = \Delta\nu_x / (\Delta p/p) \sim -6$, $\xi_y \Delta\nu_y / (\Delta p/p) \sim -8$

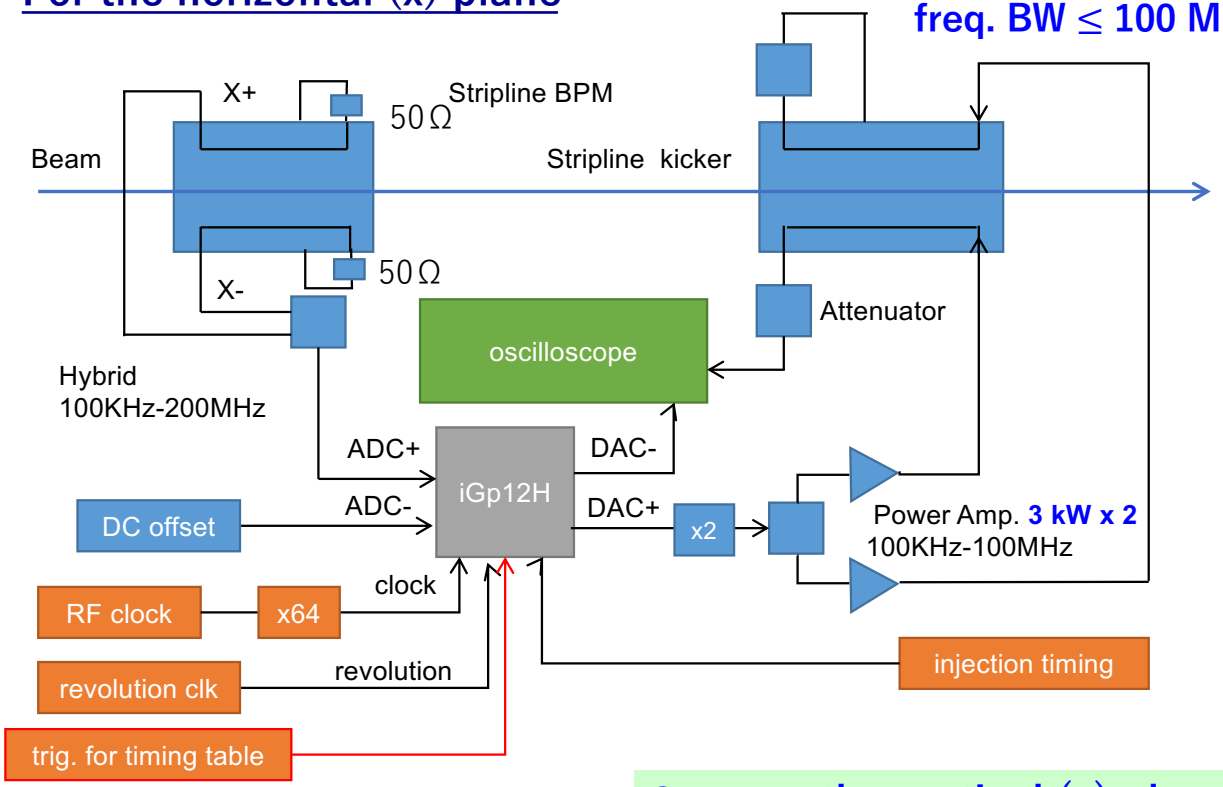


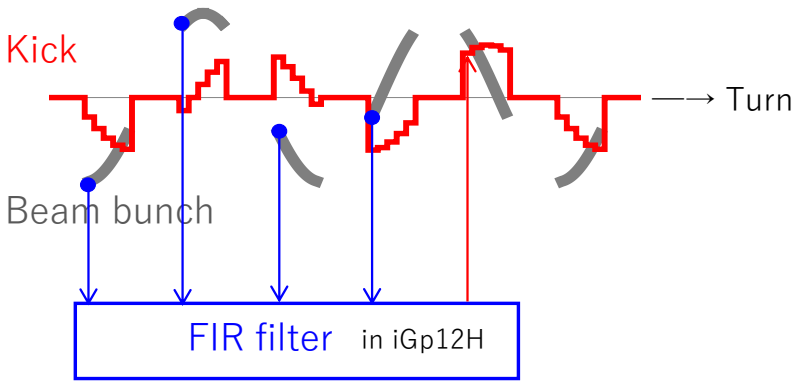
*S. Igarashi et al., PTEP **2021**, 033G01*

Transverse intra-bunch feedback

For the horizontal (x) plane

L = 0.75 m
freq. BW ≤ 100 MHz





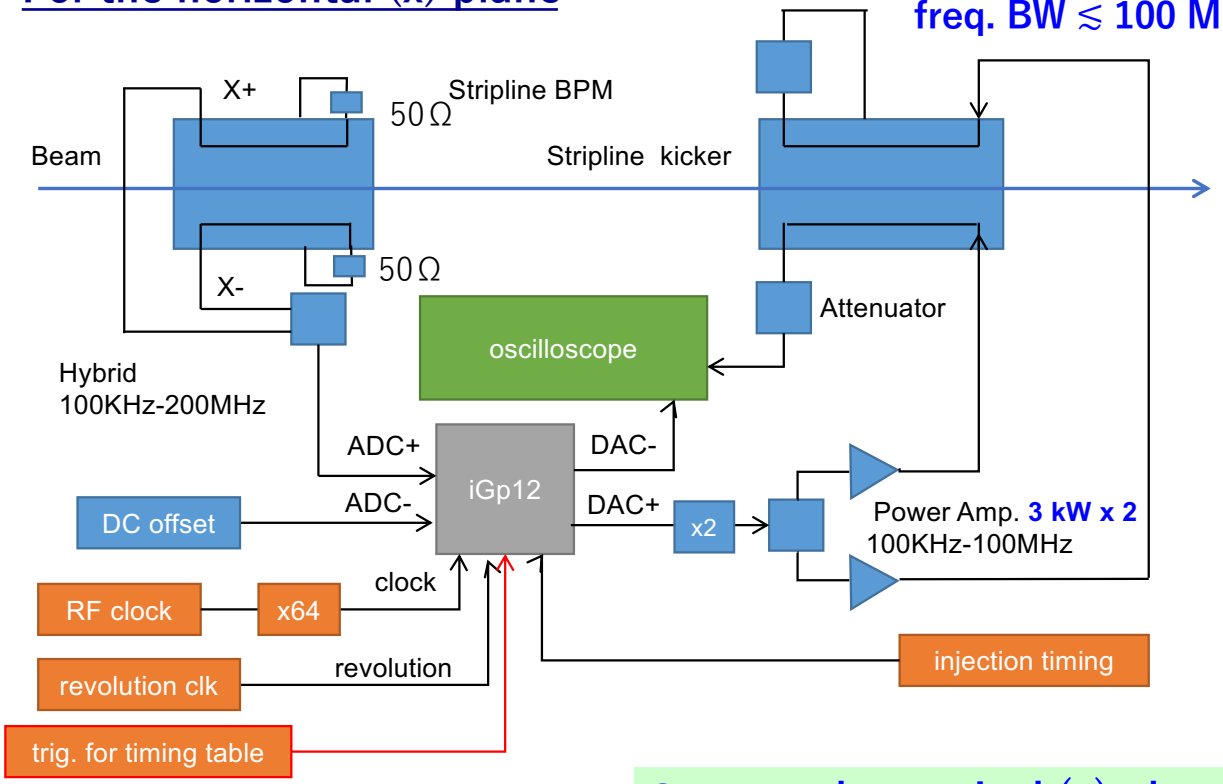
$\Delta T_{CLK} = 9.3 - 9.1$ ns

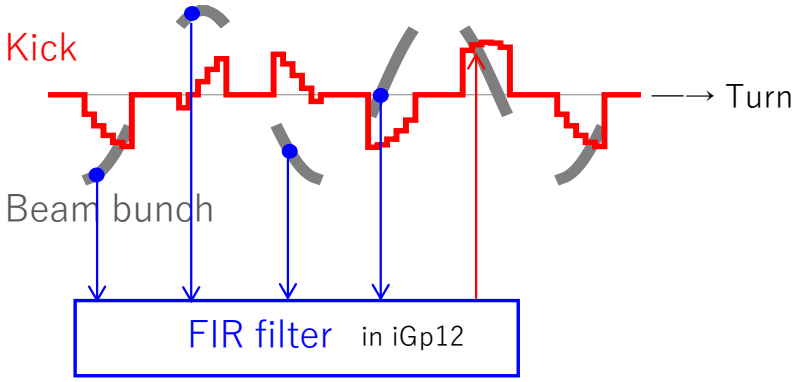
Same as the vertical (y) plane

Transverse intra-bunch feedback

For the horizontal (x) plane

L = 0.75 m
freq. BW ≲ 100 MHz





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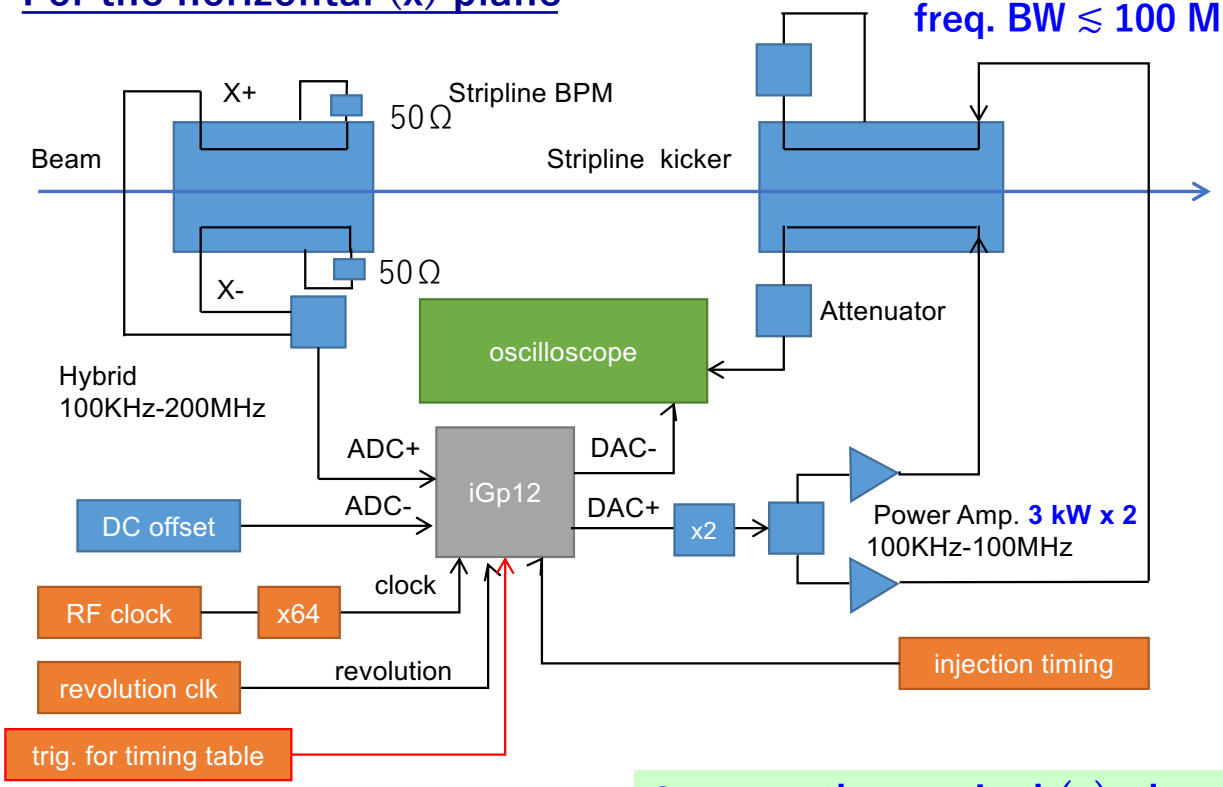
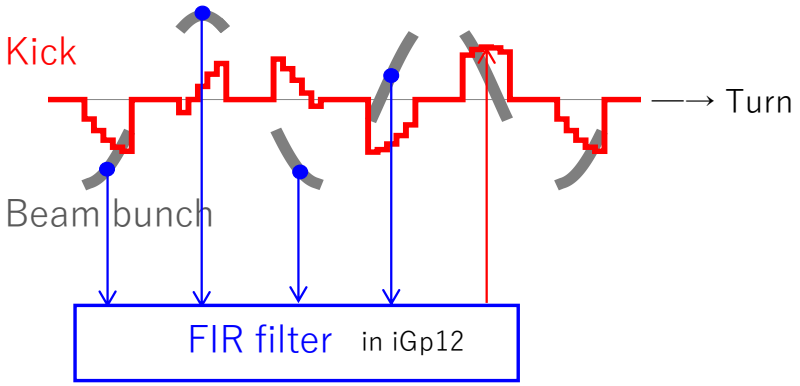
Same as the vertical (y) plane

Transverse intra-bunch feedback

For the horizontal (x) plane

L = 0.75 m
freq. BW ≲ 100 MHz





$\Delta T_{CLK} = 9.3 - 9.1$ ns

Same as the vertical (y) plane

Stability of the MR

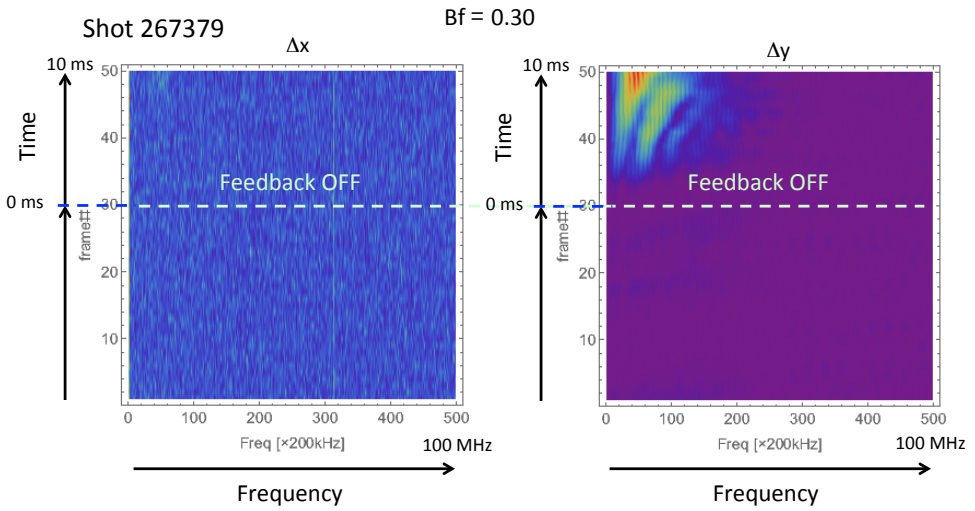
Vertical instability

Dedicated beam experiment

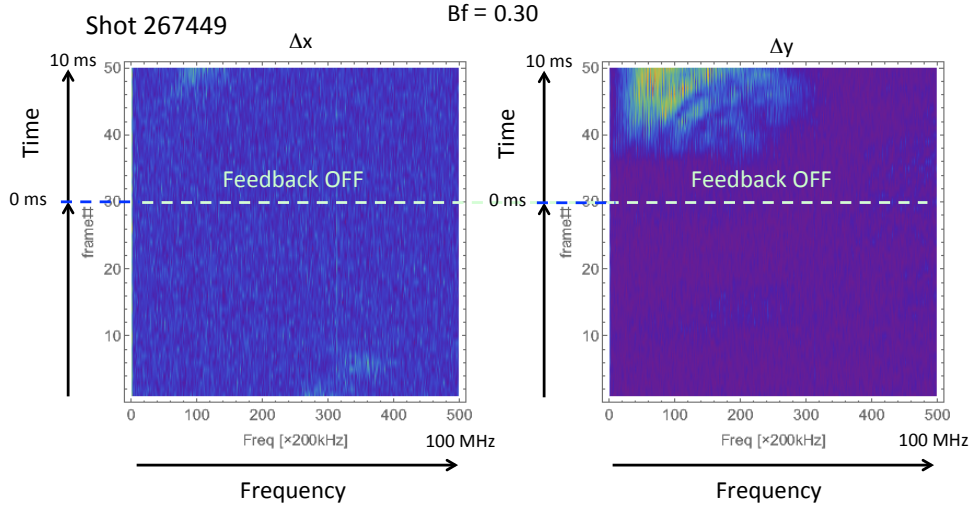
$\nu_x = 21.35$, $\nu_y = 21.45$, $\xi_x = \Delta\nu_x / \Delta p/p = 0.56$, $\xi_y = \Delta\nu_y / \Delta p/p = -0.37$

$\xi_x = (\Delta\nu_x/\nu_x) / \Delta p/p) = 0.026$, $\xi_y = (\Delta\nu_y/\nu_y) / \Delta p/p) = -0.017$

Single bunch: NB = 7.0×10^{12} p



3 bunches: equally spacing, NB = 2.8×10^{13} p (= 9.3×10^{12} x 3)

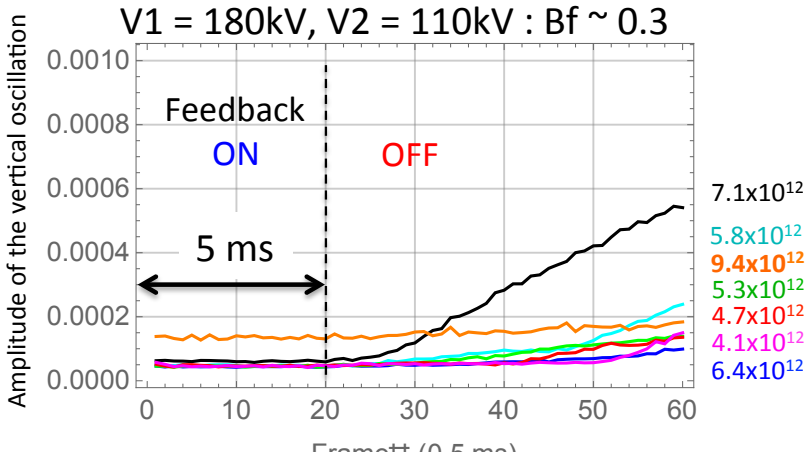


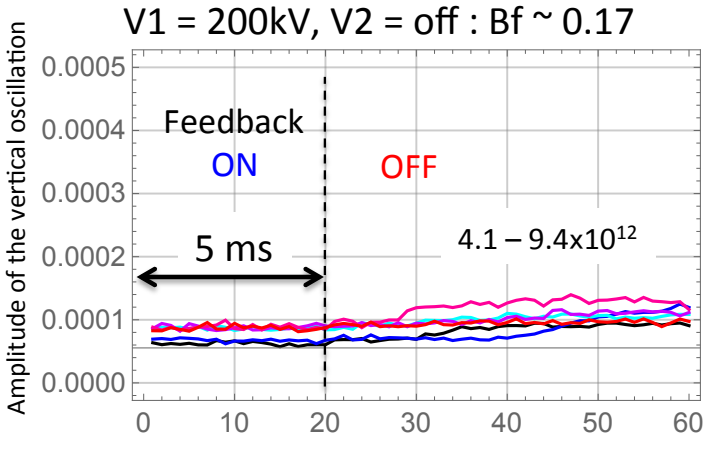
Vertical instability first occurs,

then horizontal instability occurs 10 ms after feedback OFF or later

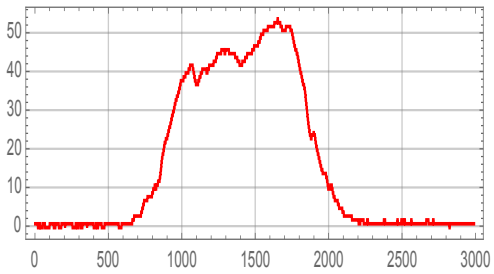
Vertical instability

Dedicated beam experiment @ $\xi_y = -0.37$, **single bunch**

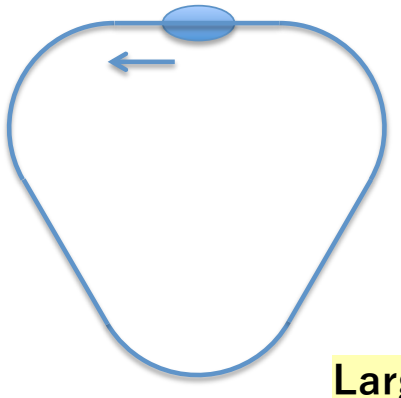




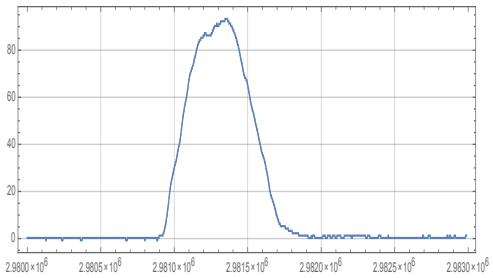
Bf ~ 0.30



1 bunch



Bf ~ 0.17



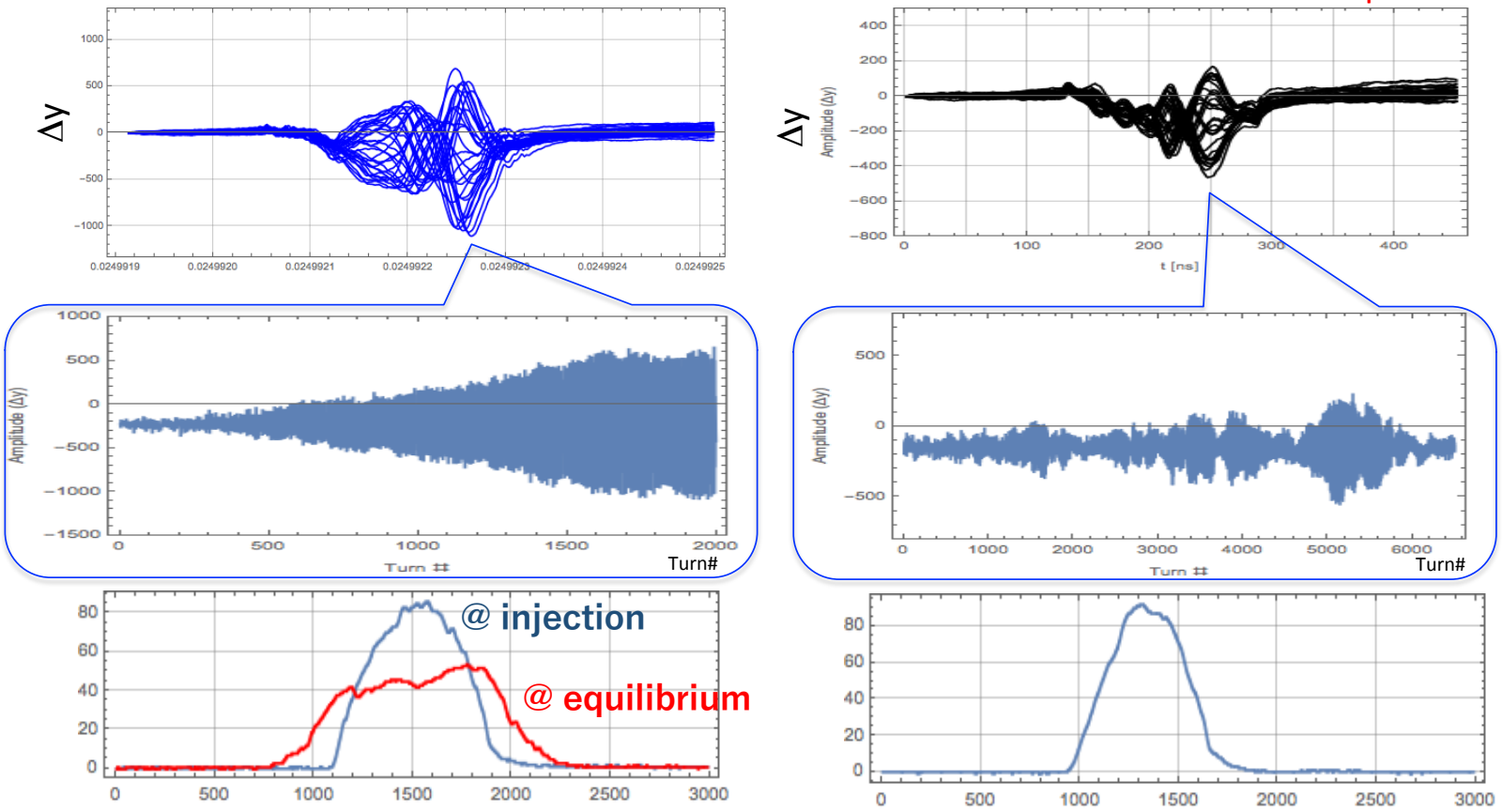
Larger peak current case is more stable

Vertical instability

Dedicated beam experiment @ $\xi_y = -0.37$, **single bunch**

Shot #379
FCT file #10
BPM file #11
WCM file #106, 107
Bf ~ 0.30 7.0×10^{12} p

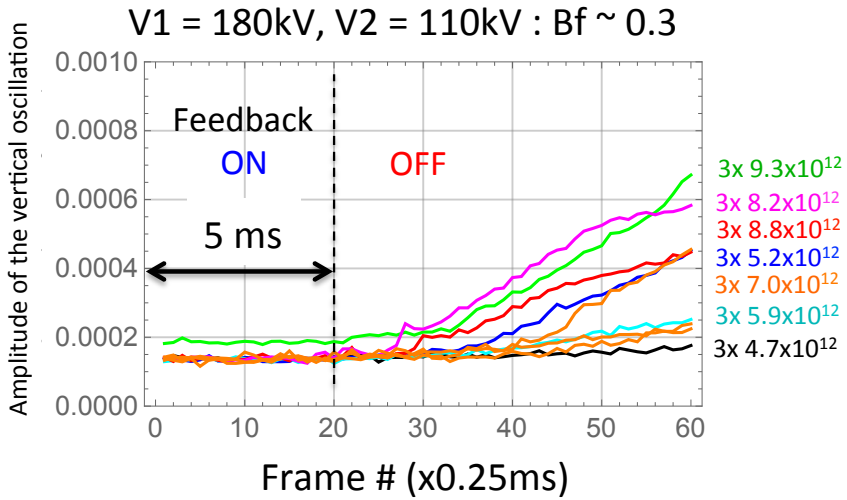
Shot #426
FCT file #86
BPM file #87
WCM file #153
Bf ~ 0.17 6.4×10^{12} p

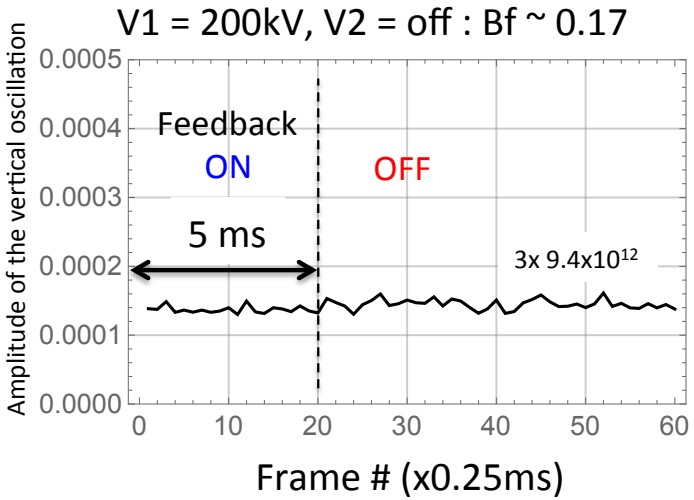


Bunch profile

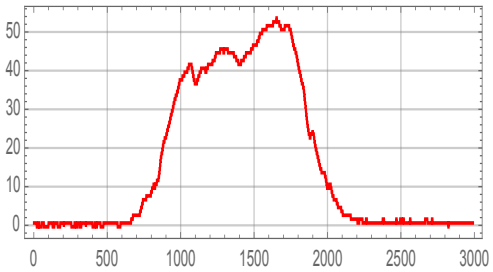
Vertical instability

Dedicated beam experiment @ $\xi_y = -0.37$, **three bunches**

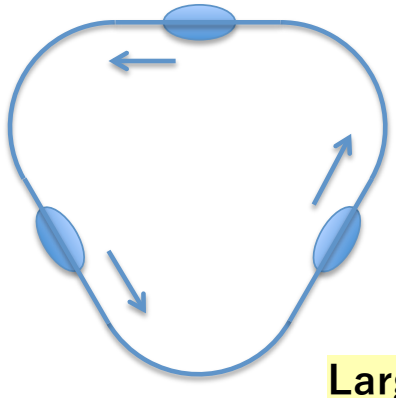




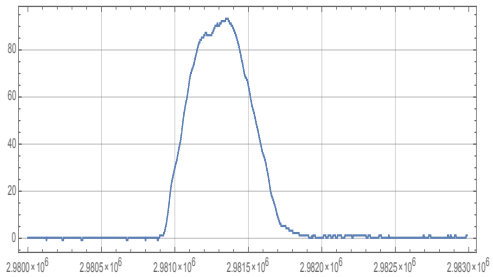
Bf ~ 0.30



3 bunches

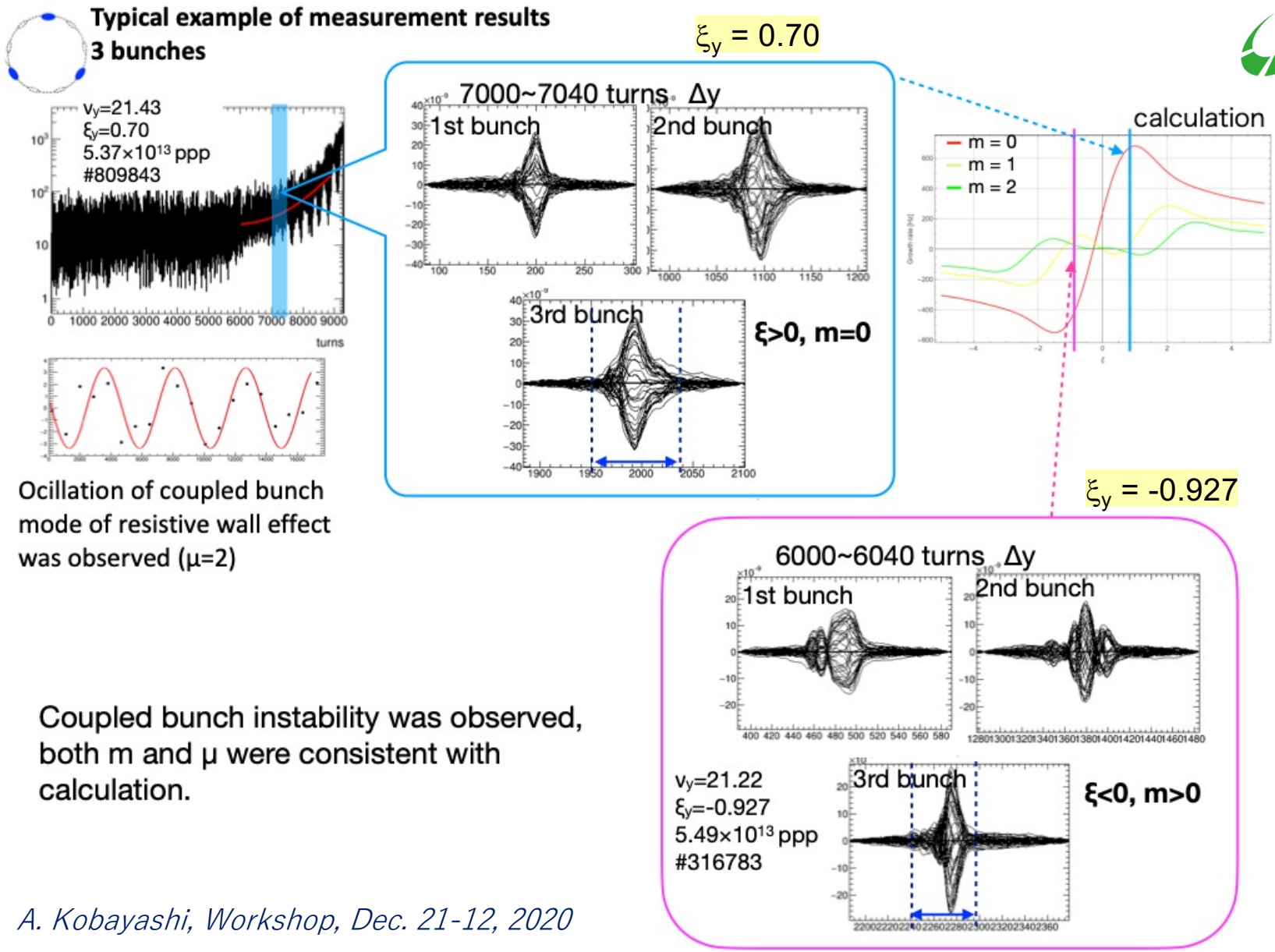


Bf ~ 0.17



Larger peak current case is more stable

Vertical instability



Coupled bunch instability was observed, both m and μ were consistent with calculation.

A. Kobayashi, Workshop, Dec. 21-12, 2020

Stability of the MR

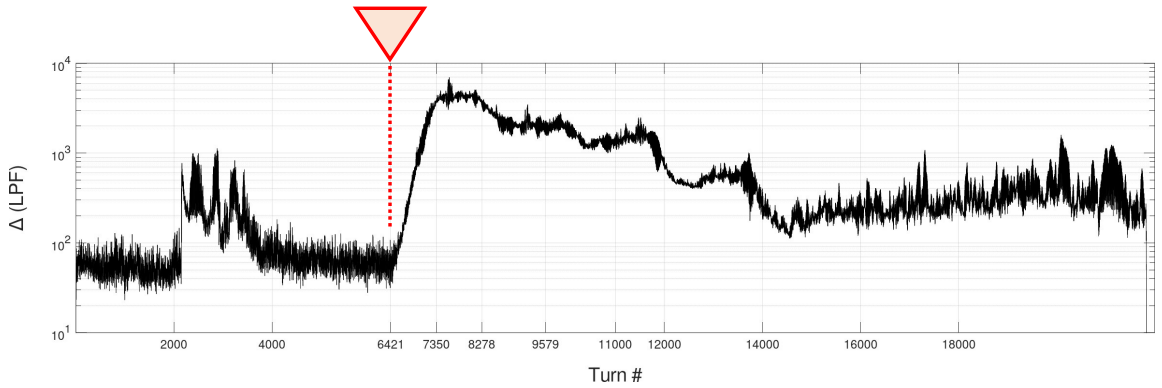
Horizontal instability

Routine operation @ $\nu_x = 21.35$, $\nu_y = 21.44$, $\xi_x = -5.89$, $\xi_y = -7.89$

↓

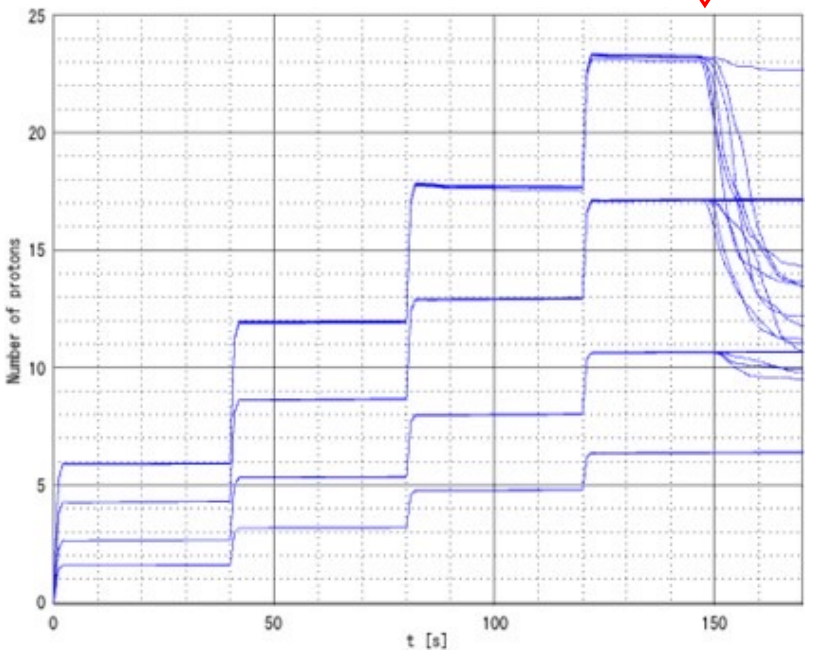
Stable

Horizontal feedback is switched off



Growth and damping at the condition of N_B=2.3E+14

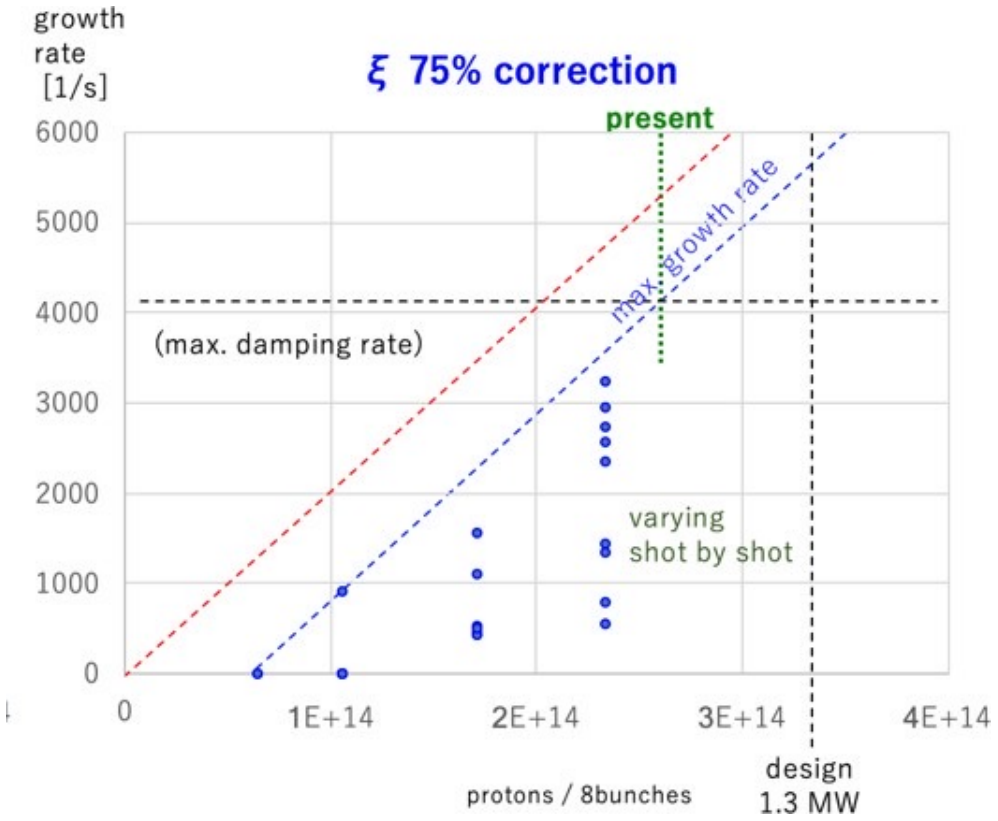
Beam loss starts due to the instability



Beam intensity variation.
Several shots are overlapped in the figure.

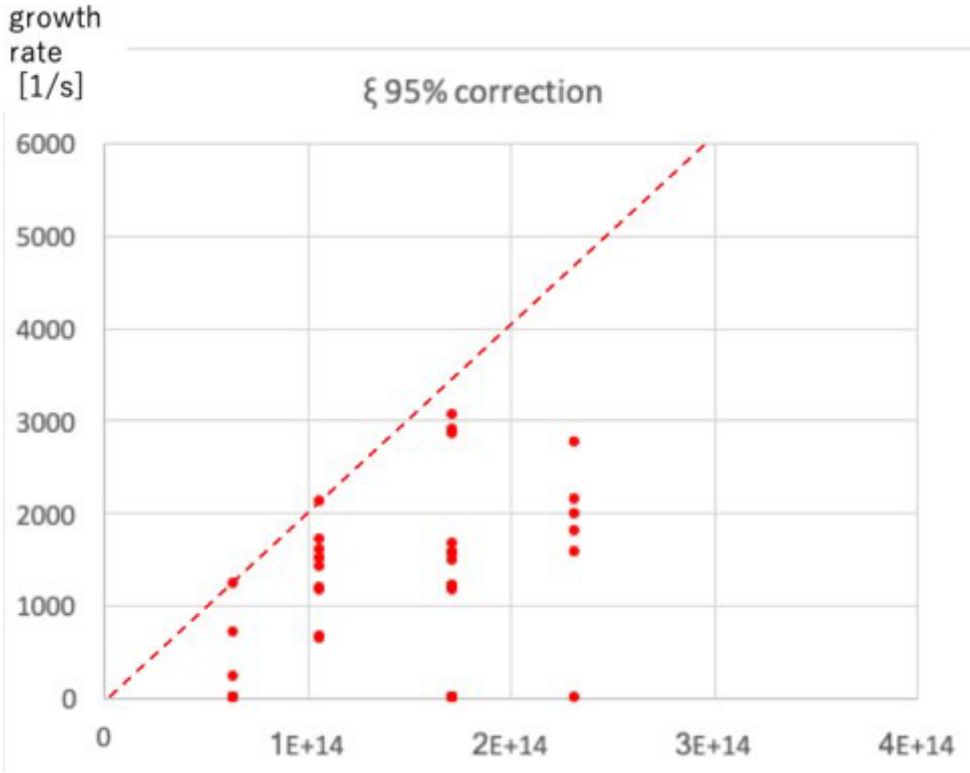
Horizontal instability

Stability of 8 bunches beam



Growth rate measured with "75% ξ correction"

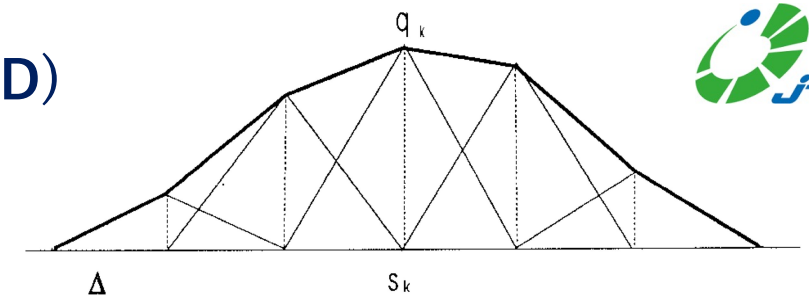
$\xi_x = -5.89$



Growth rate measured with "95% ξ correction"

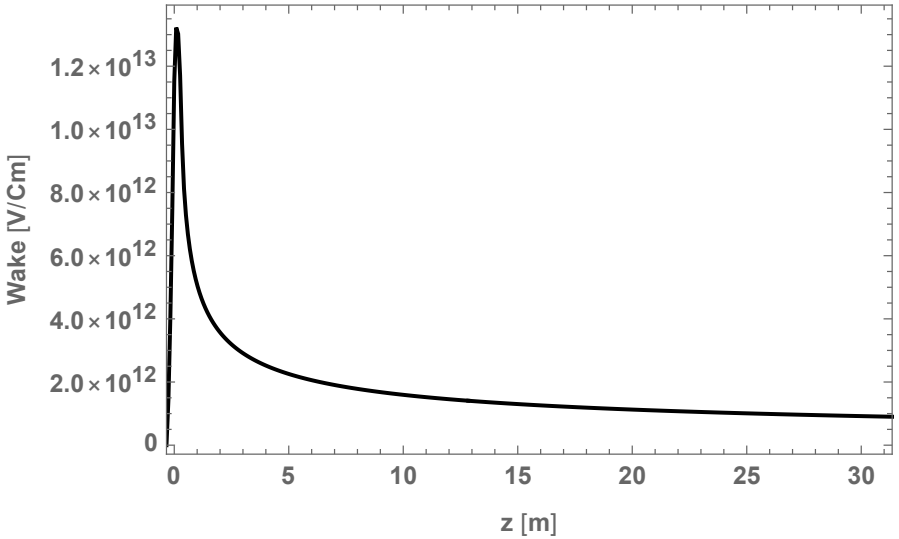
$\xi_x = -0.16$

Simulation in 2D (longitudinal + transverse 1D) with multi-triangles (without space charge effect)

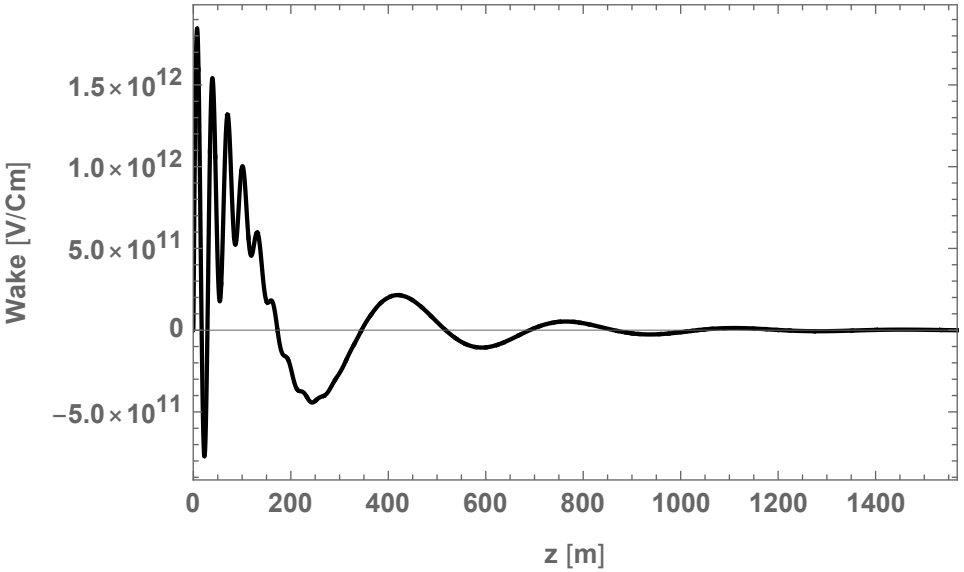


Distribution representation as sums of linear interpolating functions (M=6).
G. Sabbi, TRISIM user's guide, CERN SL/94-73(AP),1994.

Wake potentials of the unit triangle beam

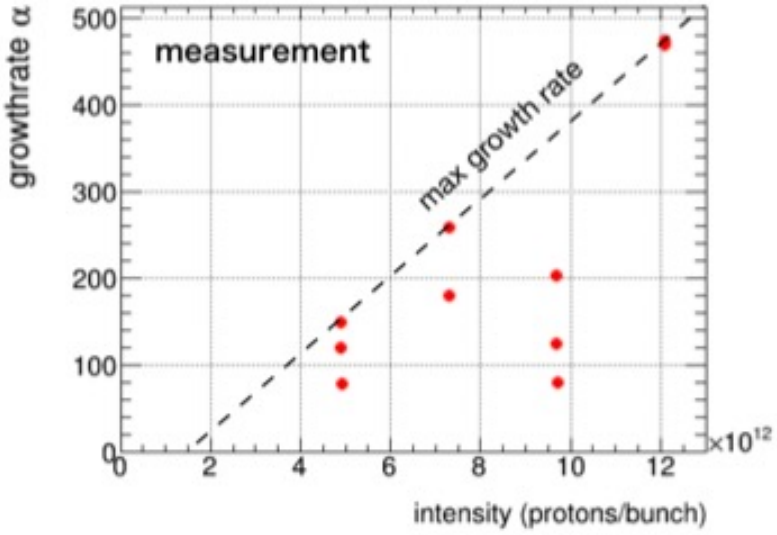


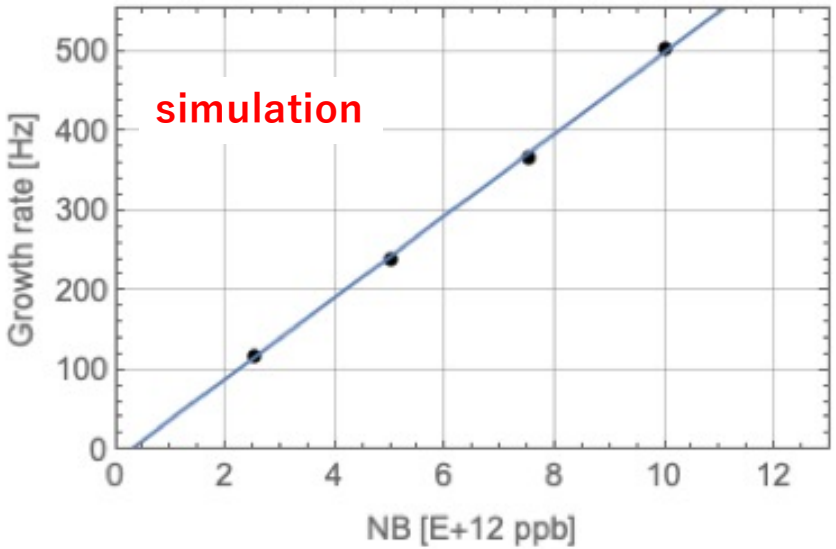
Resistive wall wake potential of the SUS316L vacuum duct, modeled with a cylindrical pipe of inner diameter 160 mm, thickness 2 mm, and length 1567.5 m.



Wake model of the five fast-extraction kickers.

Single bunch instability @ injection flat-bottom (3 GeV)





$\nu_x = 21.36$
$\xi_x = 0.64$
fundamental+2nd harmonic RF

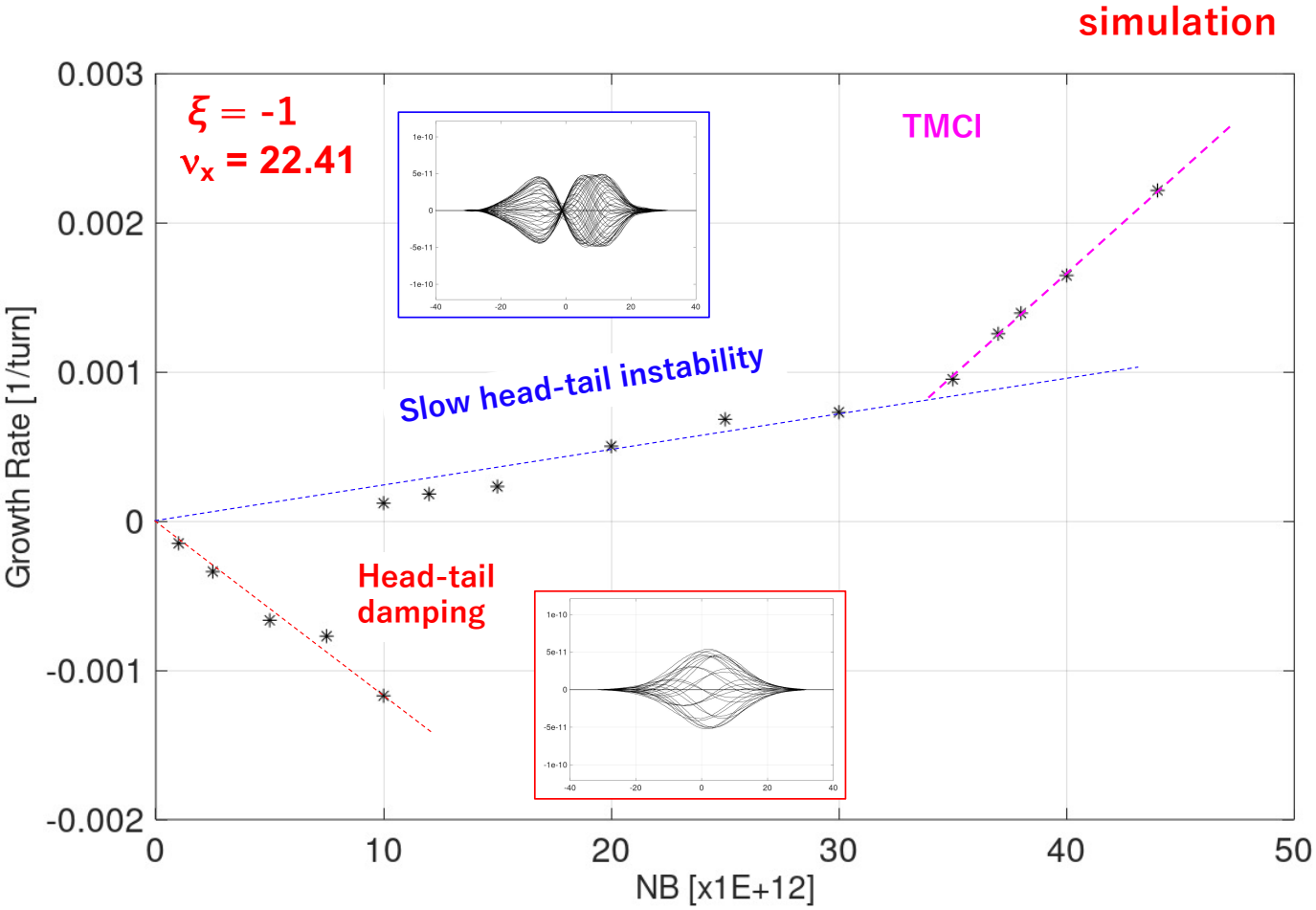
$\nu_x = 22.41$
$\xi_x = 0.64$
fundamental RF
no space charge

Comparison of simulation to the measurement.

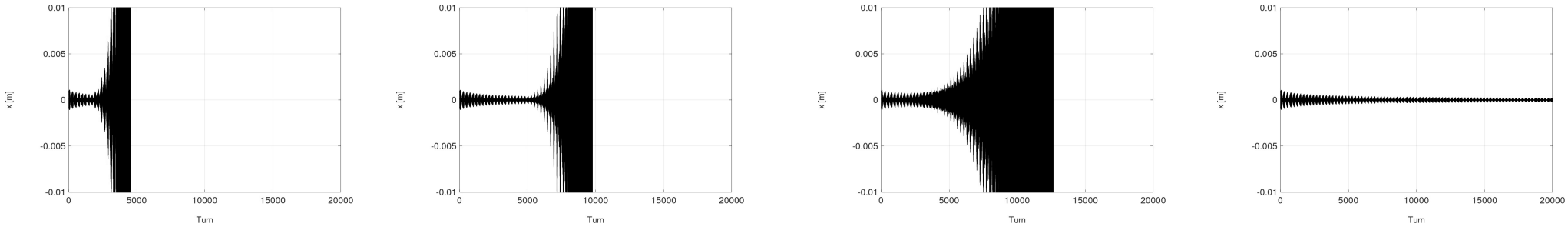
without S.C. effect → unstable

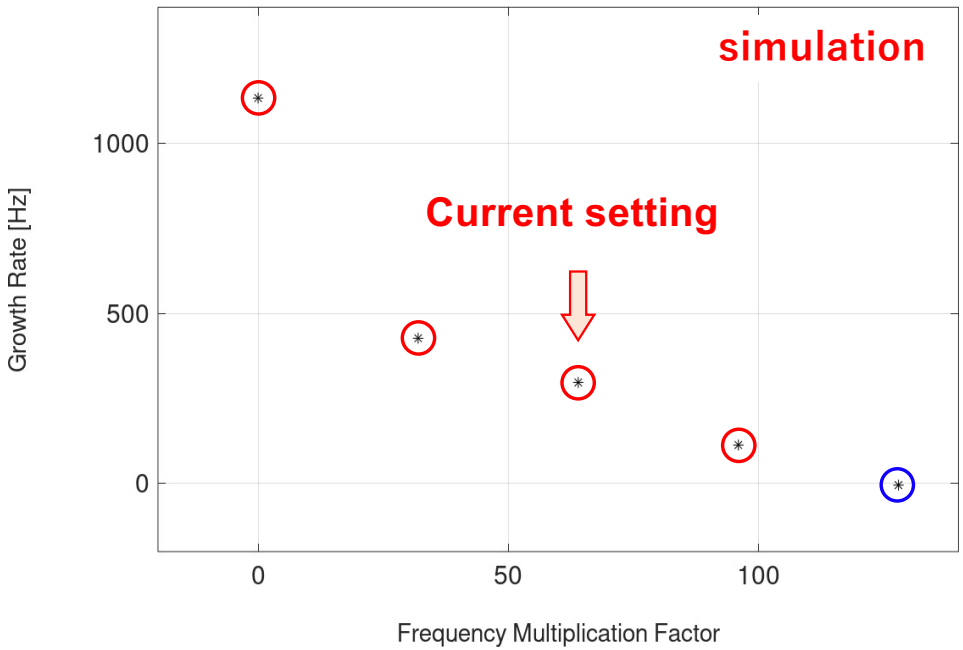
Not all the impedance sources → stable

Simulation, single bunch



Effect of the processing clock of the intra-bunch feedback system





N_B = 4.4E+13 protons/bunch

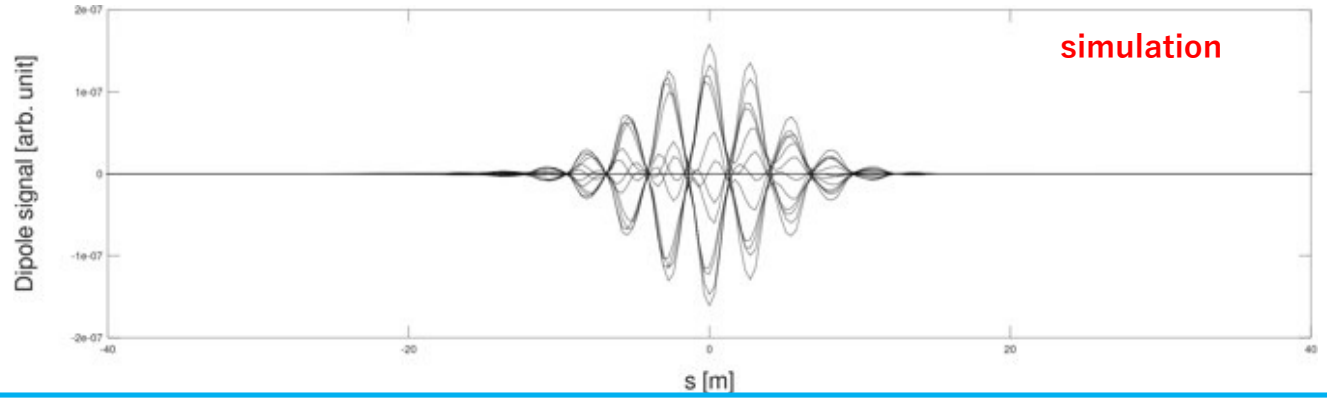
$\xi = 0$

Growth rate vs frequency multiplication factor.
The growth rate at frequency multiplication factor = 0 corresponds to operation without feedback.

Effect of the processing clock

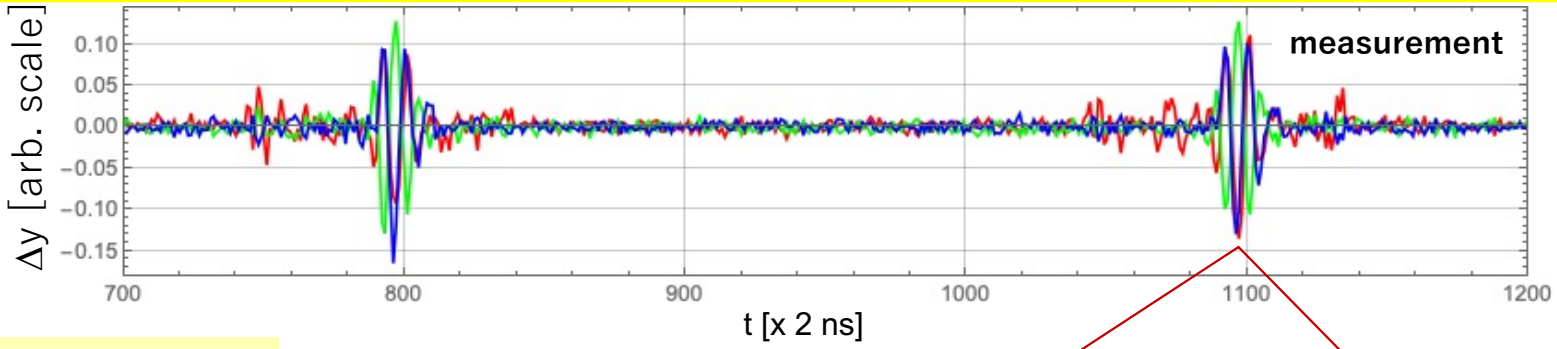
Simulation result

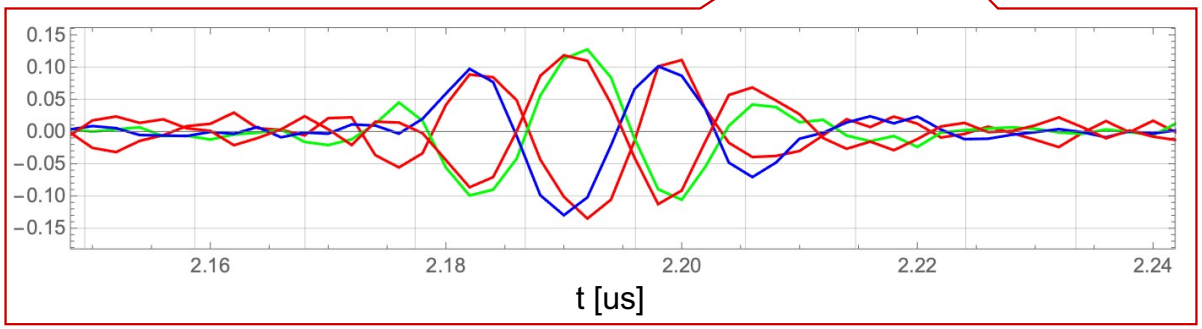
Dipole signals, overlap of 13 turns
with the processing clock
of 64 multiple of f_{RF} (simulation).



Measurement

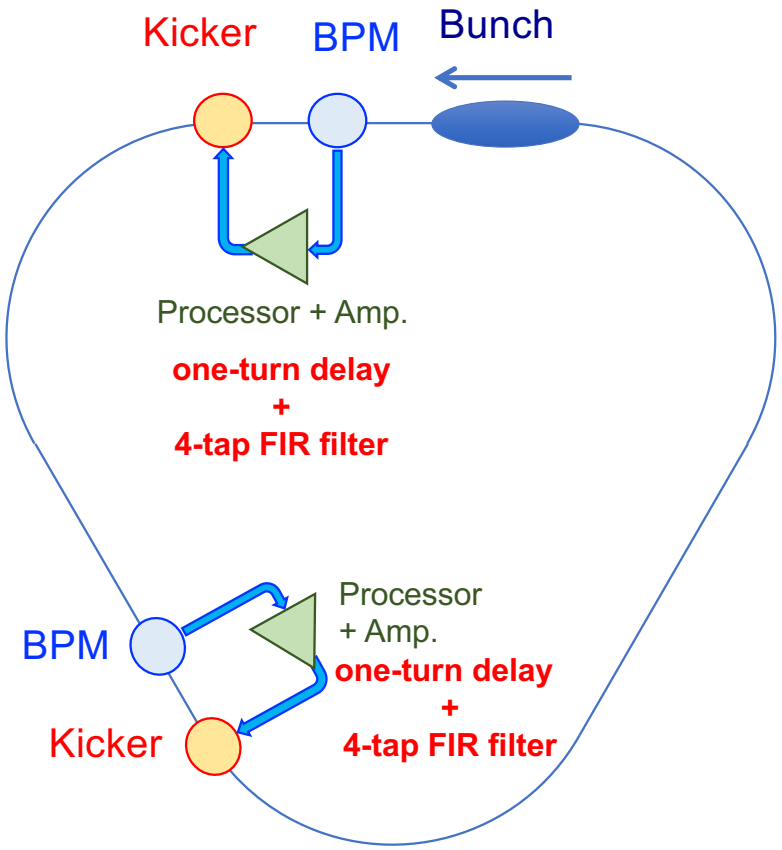
Trigger (P0) + 13 ms

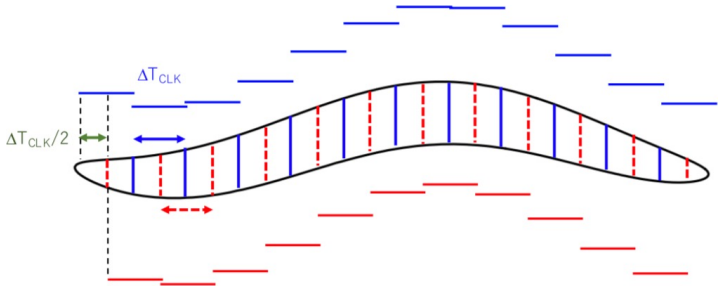




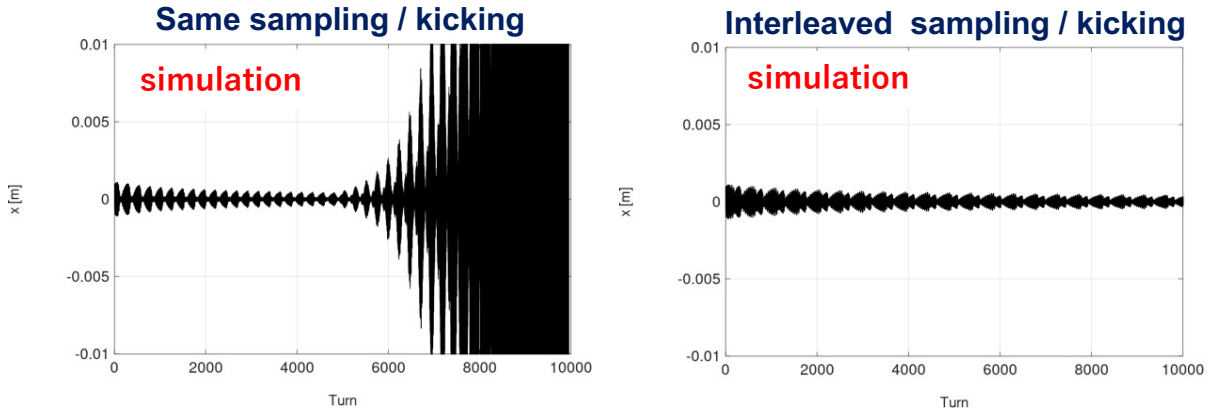
Measurement suggests
stable and unstable points
along the bunch
caused by the processing clock

Time interleaved sampling and kicking by two feedback systems





The timing of two systems is $\Delta T_{CLK}/2$ shifted.



Simulated results w/o and with the time interleaved sampling and kicking by two feedback system.
Left: the same timing
Right: interleaved sampling and kicking with $\Delta T_{CLK}/2$ shift

Summary

- ✓ Present knowledge on the transverse instabilities in the J-PARC MR is reviewed
  1. Vertical plane is more unstable than the horizontal,
     reasonable considering vacuum duct geometry
  2. Resistive wall seems dominant source, then kickers, more precisely under study
  3. Space charge instability suppression is observed
- ✓ Intra-bunch feedback system works well upto the beam power ~ 500 kW
- ✓ Above 500 kW some improvements of the feedback are necessary
  1. Time interleaved sampling and kicking
     with the current processing frequency, 64 x f_{RF} (or slightly higher 96 x f_{RF})
  2. Doubling the processing clock frequency: 64 x f_{RF} → 128 x f_{RF}