Multi-bunch acceleration experiment at KURRI FFAG
(Simulation updated)

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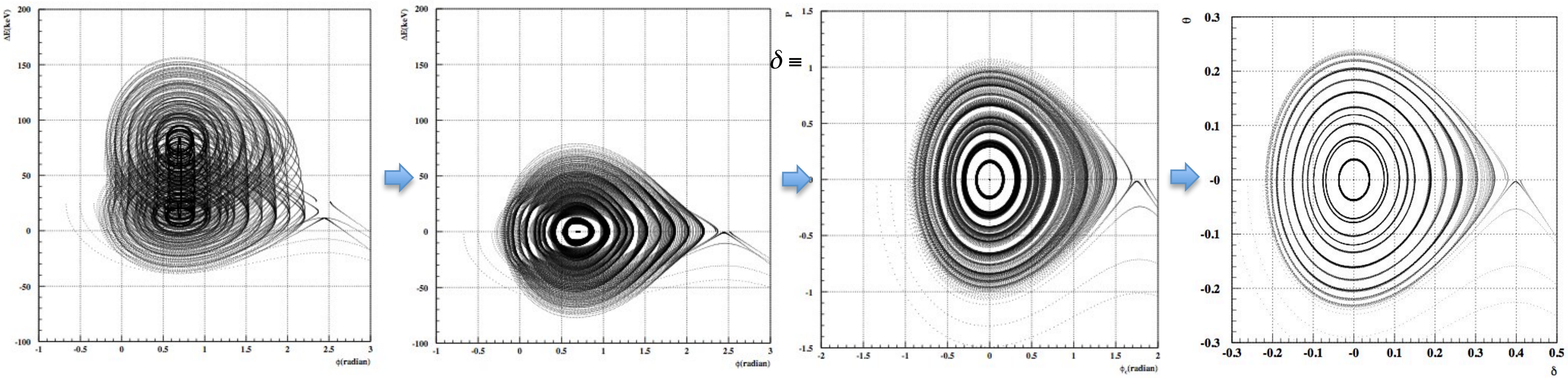
Summary of status in the last meeting

- Multi-bunch acceleration was simulated in KURRI booster FFAG
- Up to 15 bunch acceleration was demonstrated, and found no significant beam loss.
- As the number of bunch increases, the required peak voltage drops compared to ($n_{bunch} \times V_{bunch}$). In 10 bunch case, ~ 1/2
- The saturated and deformed rf can still accelerated beam as long as the fraction of deformed rf is below 5% of total rf wave, though slight blow-up is observed.
- The dynamics of multi-bunch acceleration was not fully understood

Invariant longitudinal phase space

- In the previous longitudinal phase space plot (dE, ϕ) , several ambiguity was included (central energy and actual ϕ_s due to the fitting error of rf pattern).
- (dE, ϕ) phase space is not invariant during acceleration (change of ν_s, adiabatic dumping). ➔ To understand the dynamics, longitudinal phase space should be plotted in an invariant form.



(ϕ, ΔE)
E_0 uncorrected

(ϕ, ΔE)
E_0 corrected

(θ, P)
ϕ_s corrected.

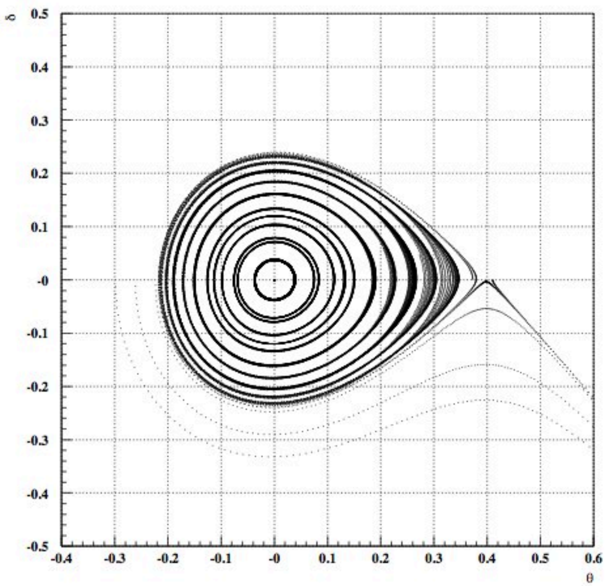
$$P \equiv h|\eta|\nu_s\delta$$
$$\delta \equiv \Delta p / p$$
$$\theta \equiv \phi - \phi_s$$

$(\delta_{inv}, \theta_{inv})$

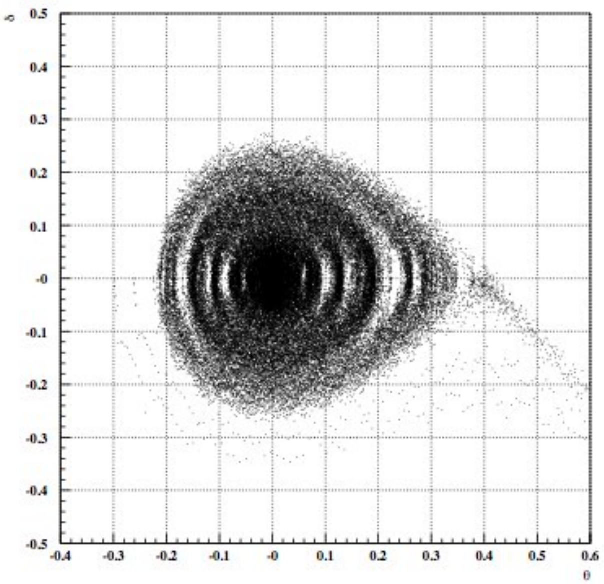
$$\delta_{inv} \equiv \delta / (\alpha\sqrt{\eta / \nu_s})$$
$$\theta_{inv} \equiv \theta / (\alpha\sqrt{\nu_s / \eta})$$
$$\alpha \equiv \sqrt{\omega_0 / \pi\beta^2 E}$$

Multi-bunch acceleration (number of bunch dependence)

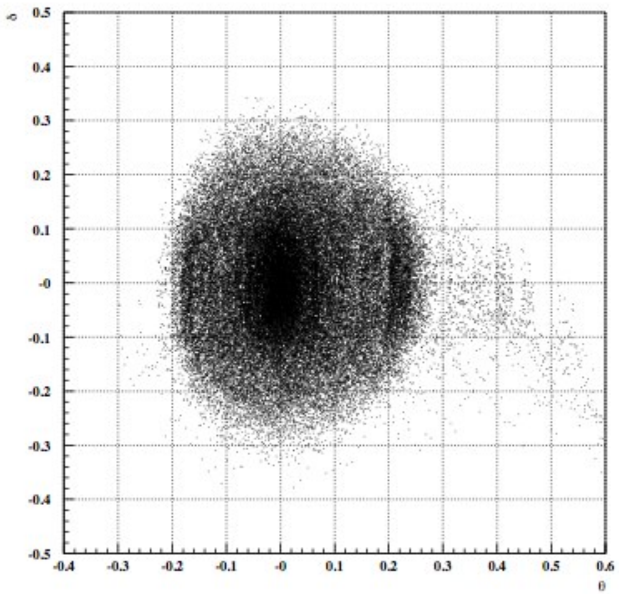
In invariant longitudinal phase space, phase space motion in multi-bunch acceleration was plotted



1 bunch



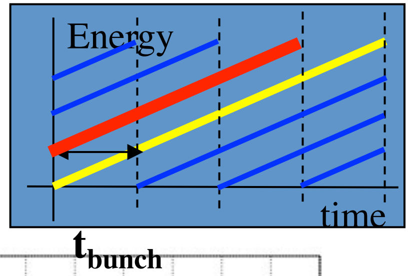
6 bunch
(bunch separation:
250 μsec)

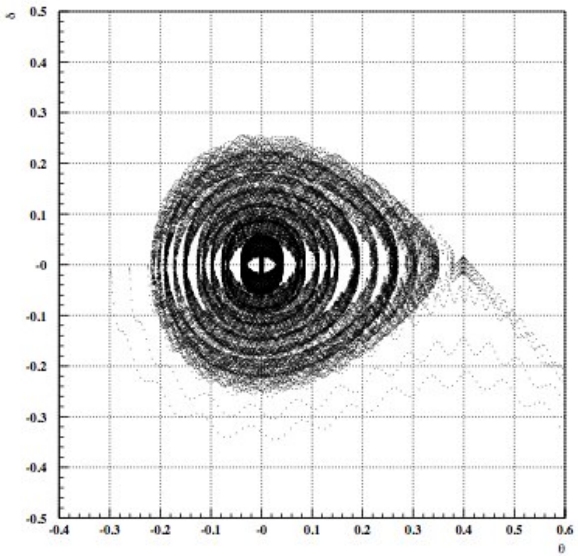


15 bunch
(bunch separation:
100 μsec)

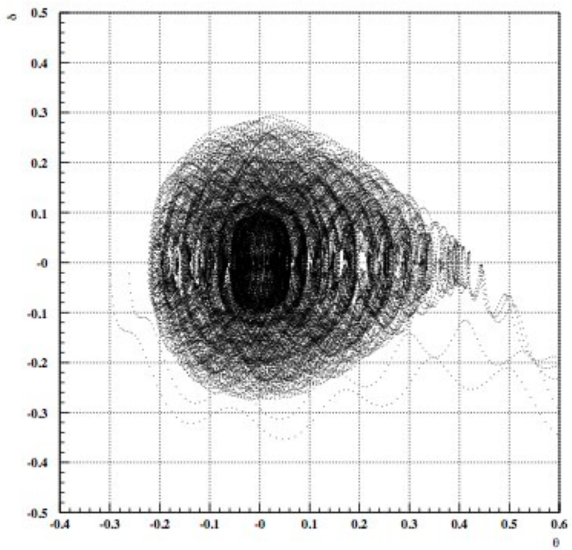
Multi-bunch acceleration (2-bunch)

Varying the bunch separation in 2 bunch acceleration, longitudinal phase space motion was examined.
As the

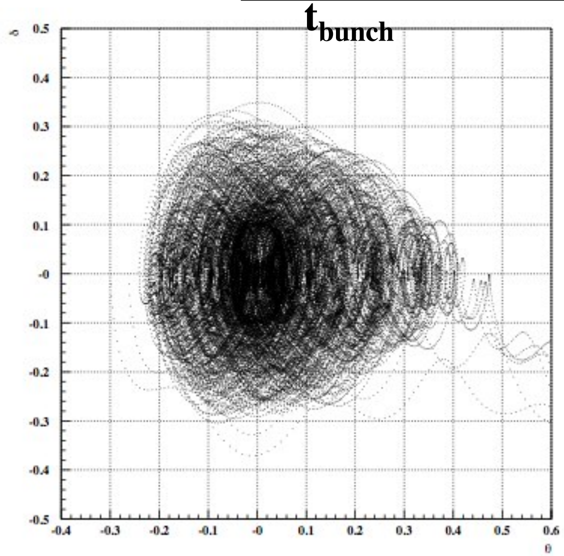




bunch separation
 : 250 μsec)



bunch separation
 : 100 μsec)

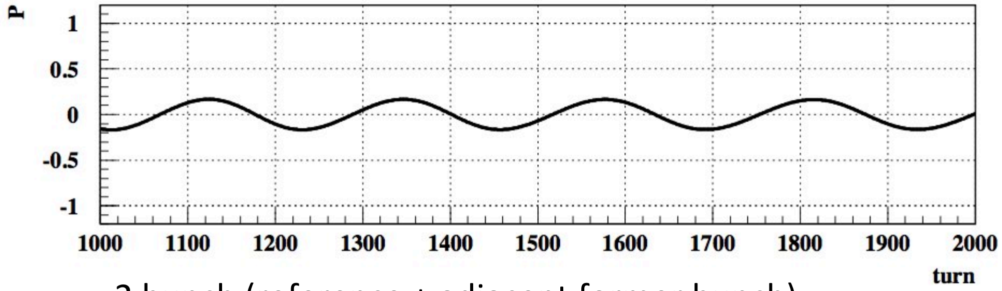


bunch separation
 : 70 μsec)

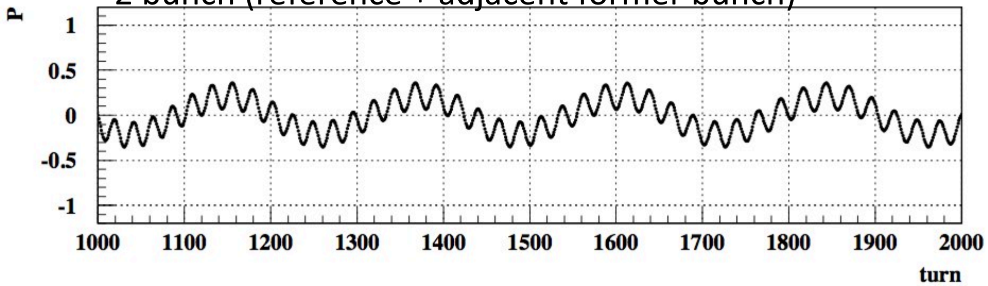
Multi-bunch acceleration(single particle motion)

- To understand the dynamics, single particle motion was investigated fixing the bunch separation and changing the number of bunch.
- The perturbation is linear and only adjacent 2 bunch mainly contribute the perturbation. (See the next slide)
- Dominant factor is the bunch separation. Thus, as long as the bunch separation is fixed, the dynamics is basically similar to the case of 3 bunch acceleration

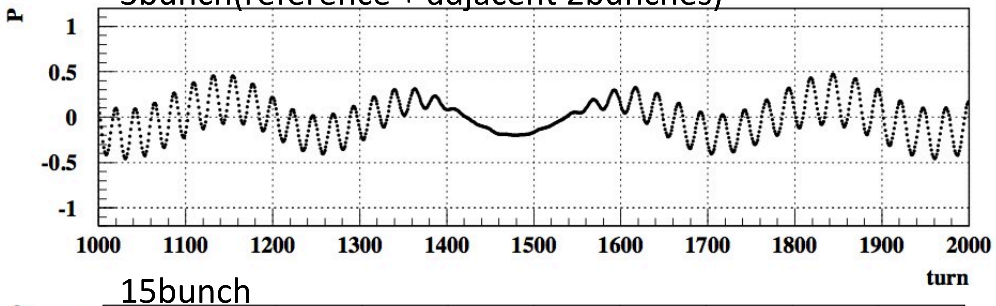
1 bunch



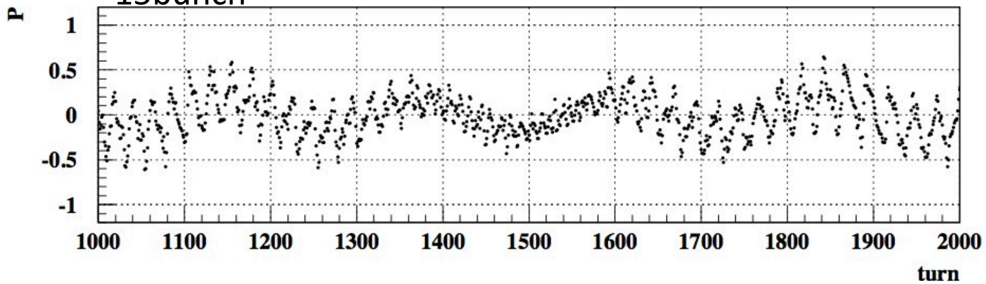
2 bunch (reference + adjacent former bunch)



3bunch(reference + adjacent 2bunches)

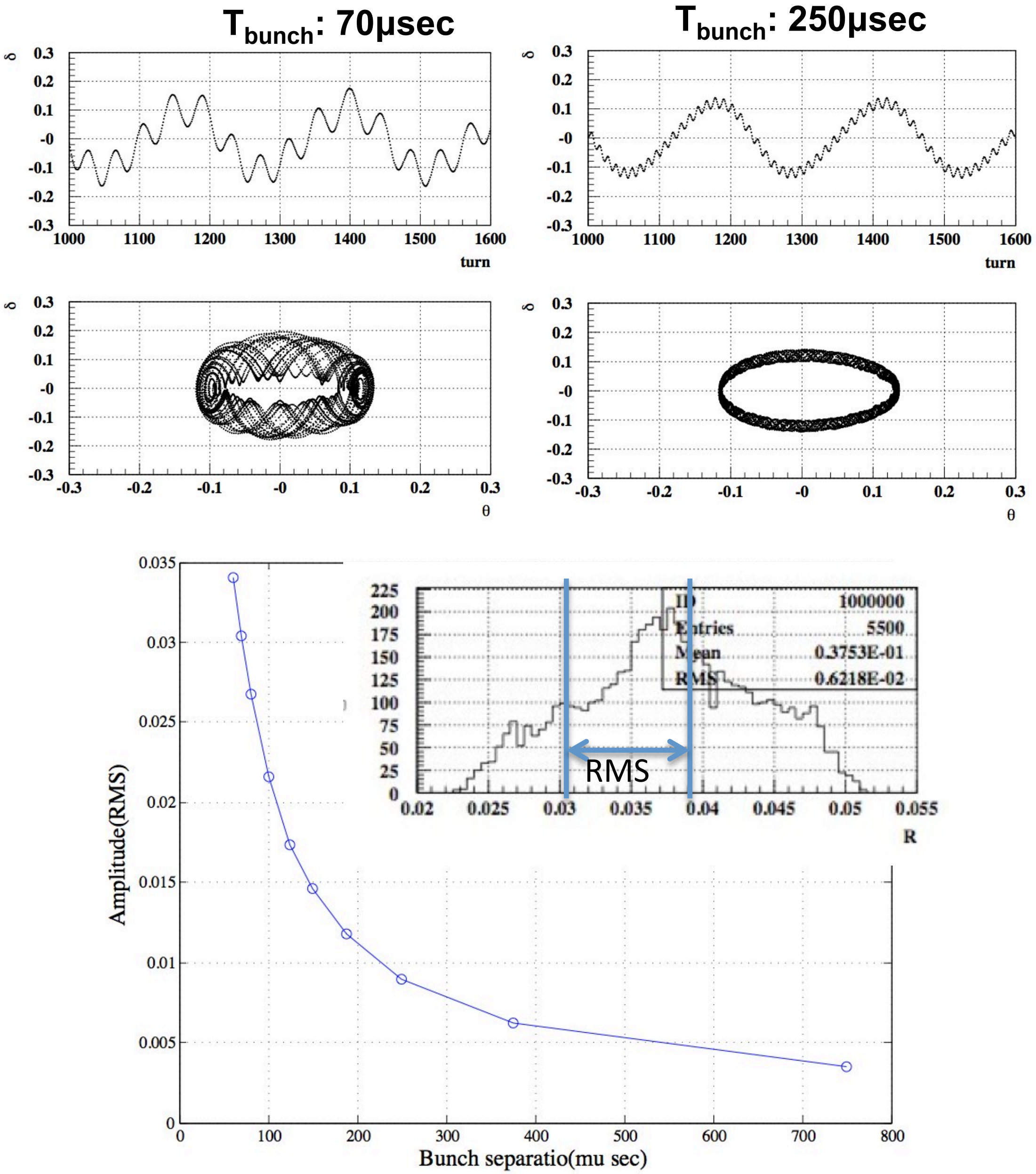


15bunch



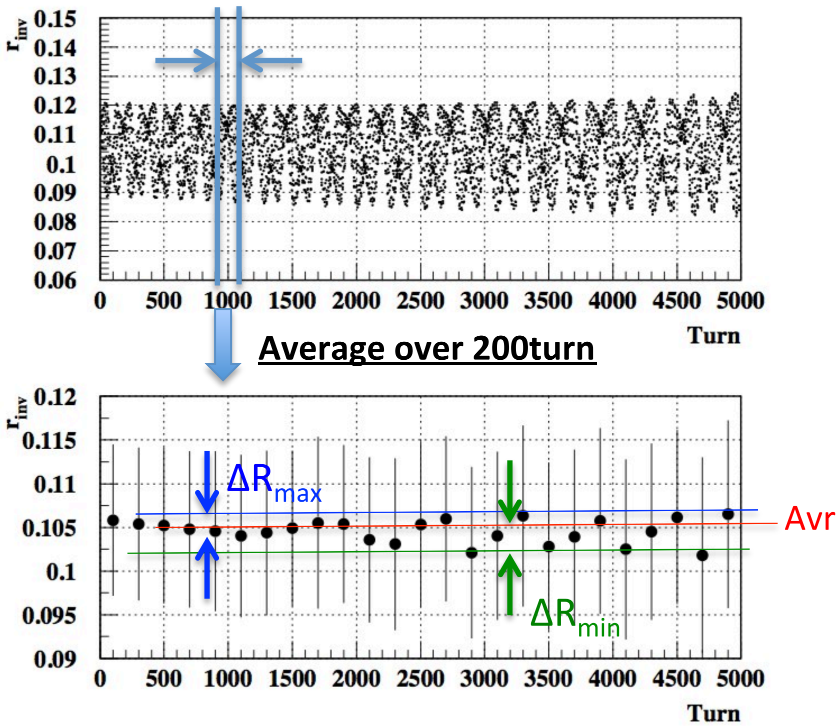
Bunch separation dependence

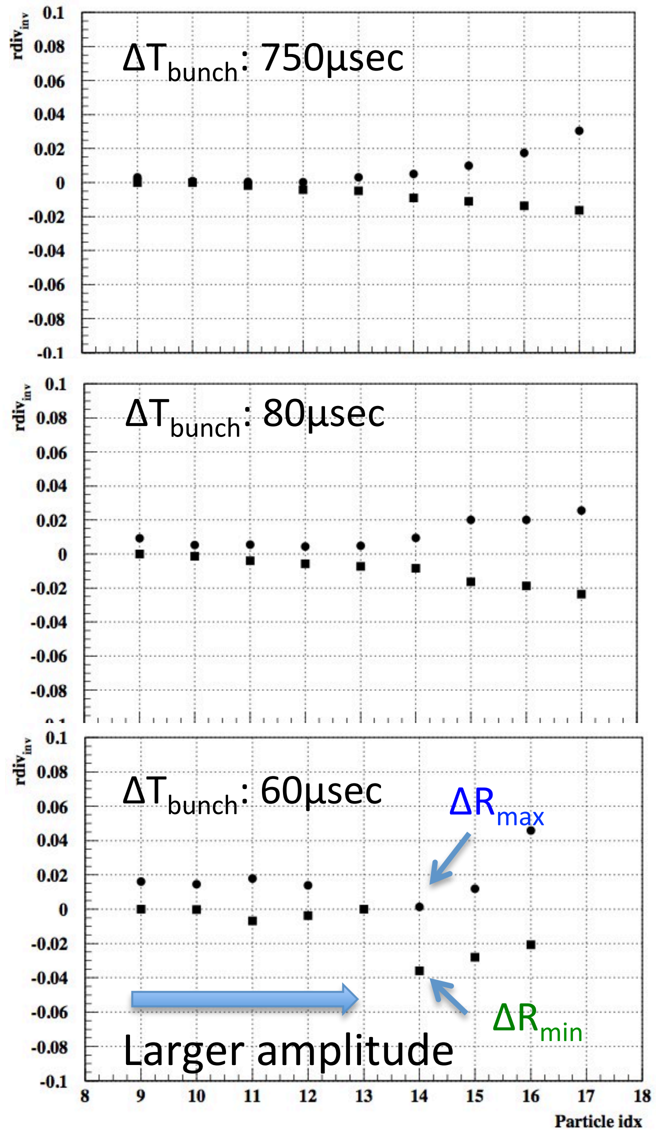
- To examine the bunch separation dependence of perturbation of synchrotron oscillation, radial distribution of small amplitude particle in invariant phase space was adopted as a measure.
- The results supports that the adjacent bunches dominantly determined the perturbed synchrotron motion
- Basically, the dynamics can be explained with ordinary synchrotron oscillation.



Bunch separation dependence (2)

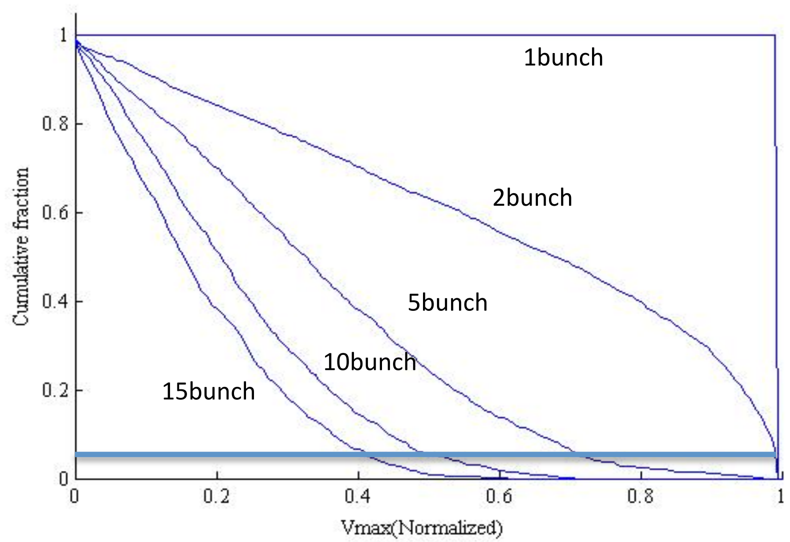
- As a measure of beam distortion, the maximum deviations of perturbed beam envelope was plotted as a function of amplitude.
- Below ΔT_{bunch}: 80μsec, bucket collision was observed. (consistent with the synchrotron oscillation theory)

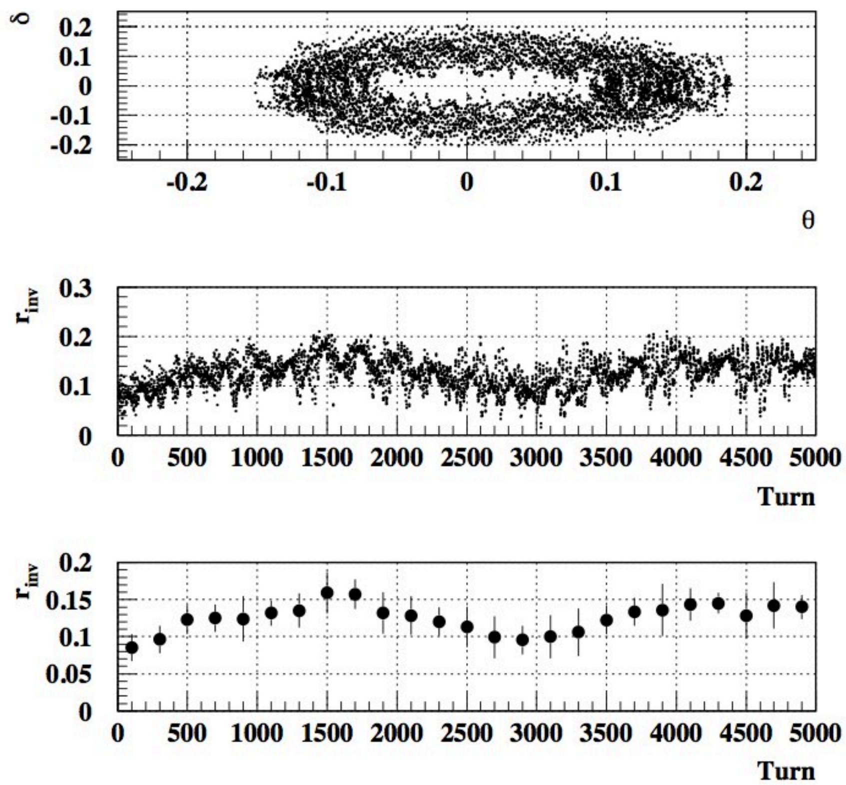




Saturation effect

- By clipping the rf voltage, output saturation was introduced in the simulation
- Up to ~5% of rf error, beam can accelerated to the end without significant beam loss (similar study of 2-bunch motion was carried out)
- Above the error level, significant beam blow-up is observed
- The beam loss/blow-up mechanism is not clear at the moment.

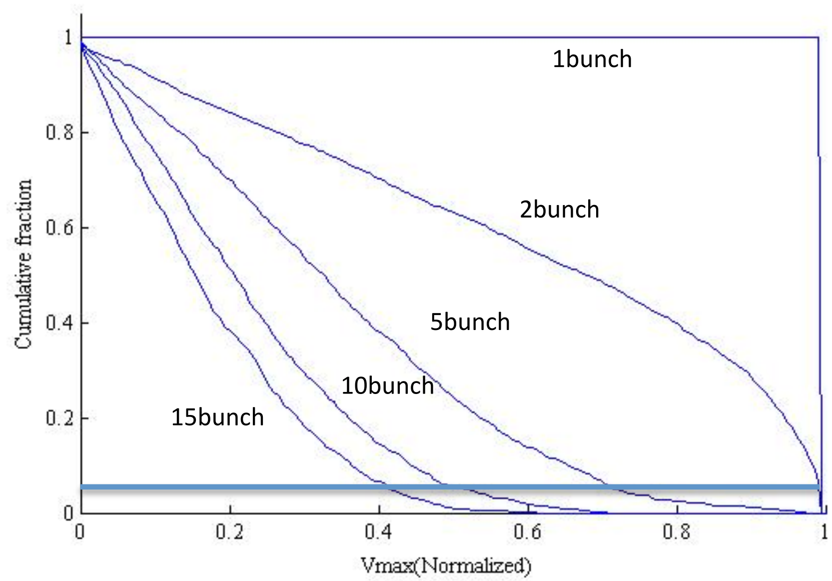




Typical beam blow-up(10bunch, SF:0.5)

How efficient with an existing rf system?

- In the case of 10 bunch acceleration, peak rf voltage ~$0.5 \times n_{bunch} \times V_{bunch}$
➔ it is equivalent to double the available rf voltage.
- Thus, if the peak voltage is the limiting factor, the acceleration rate of a bunch is 1/5 of single bunch acceleration in 10 bunch acceleration
- In result, the intensity is doubled (1/5 × 10 = 2)
- On the other hand, the rf power is 2/5 compared to single bunch acceleration. ($1/5^2 \times 10$)
- Thus, rf power wise, it is as expected factor of 10 more efficient [2 × 2 × (2/5)]



Cumulative fraction of normalized maximum voltage in rf bucket