Multi-bunch acceleration experiment at KURRI FFAG

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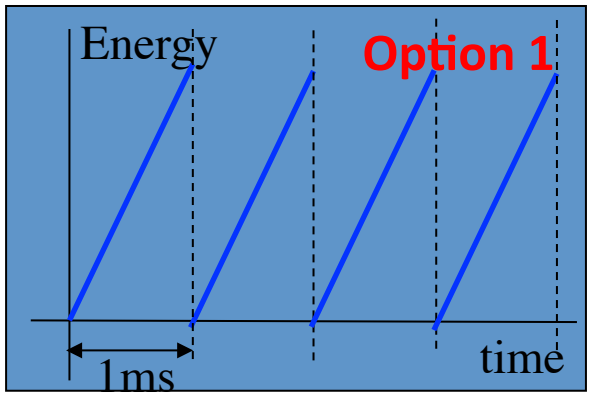
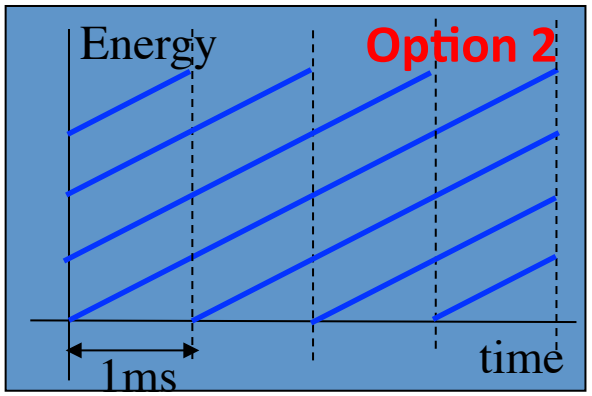
Introduction

- For high intensity application such as ADSR, high repetition operation is a requirement to diminish the influence of space charge force
- For the realization of high repetition rate operation in circular machine, rf is a real obstacle , since $P=V^2/R$

  One approach is high Q cavity (PAMELA ferrite rf cavity : Q~60)
- The square nature of the rf power causes blowup of average power and peak power. Thus, it results in the surge of running cost and initial cost
- In FFAG, due to the fixed field, beams of different energies can be circulated simultaneously.
- In broad band rf cavity such as MA cavity, multiple frequencies can be generated with single cavity.
- Thus, in FFAG, multibunch acceleration with broadband cavity can be employed as an alternative option for acceleration

Multi-bunch acceleration : average power





Low Q cavity (ex MA) can mix wide range of frequencies

$$P = \int \frac{(\Sigma V)^2}{R} dt$$

$$(\Sigma V)^2 \equiv (\Sigma V_i sin[f_i(t)])^2$$

$$= \sum_i (V_i sin[f_i(t)])^2 + \underbrace{\sum_{i \neq j} (V_i sin[f_i(t)] \cdot V_j sin[f_j(t)])}_{\frac{1}{T}\int dt \longrightarrow 0}$$

Option 1: $P \propto N_{rep}^2$

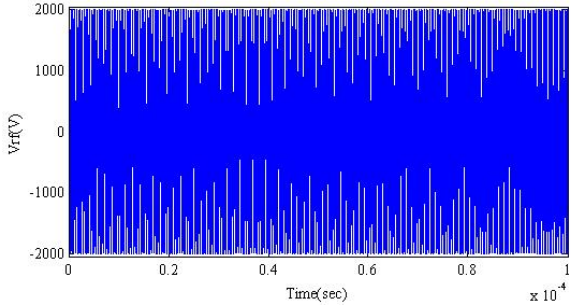
Option 2: $P \propto N_{rep}$

Multi-bunch acceleration is preferable from the viewpoint of efficiency and upgradeability

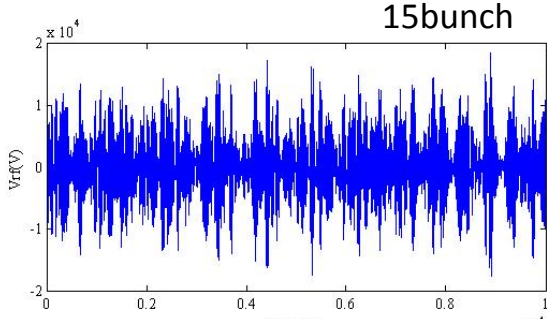
Multibunch acceleration : peak power

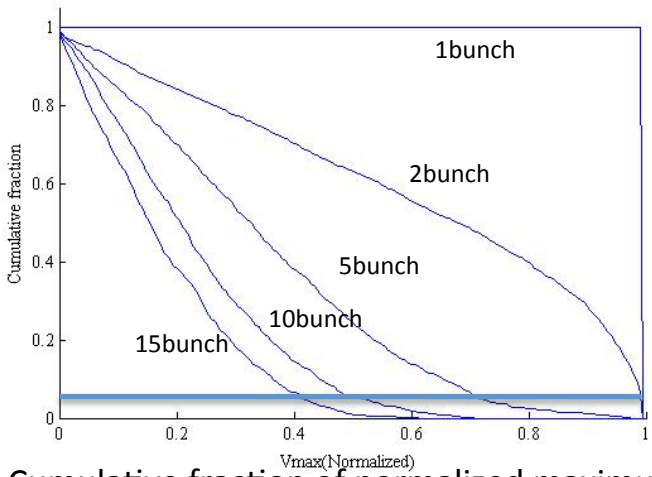
- The voltage distribution of the multibunch acceleration is completely different from that of single bunch acceleration
- As the number of superposition increases, the high amplitude fraction gets reduced drastically.
  Ex. for 15bunch case, 99% of bunches, the peak rf voltage is below 0.5*(nbunch*Vrf)
- According to tracking study of multi-bunch acceleration with voltage cut-off, up to ~5% of rf voltage error is tolerable.
- In result, the peak voltage can also be reduced considerably in multibunch acceleration(~60% reduction in 15bunch case. ➔peak power wise, ~85% reduction)

1bunch



15bunch

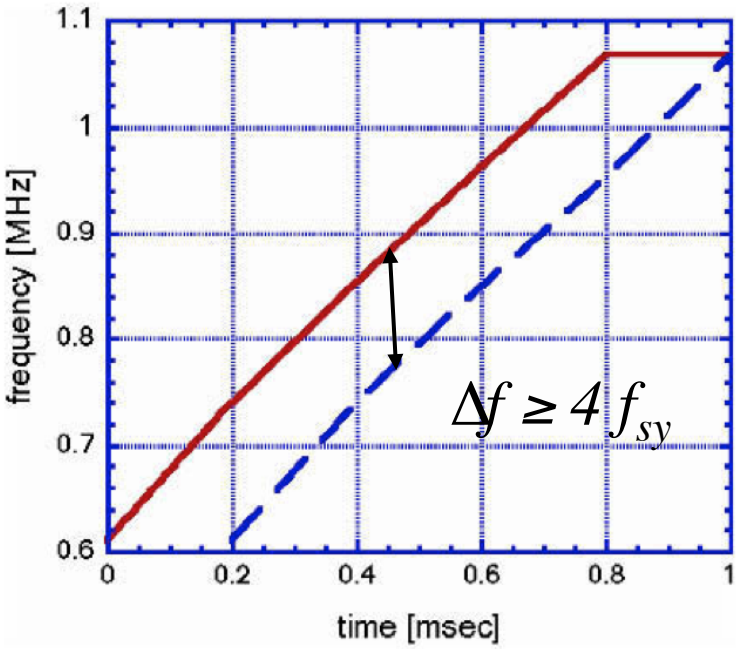


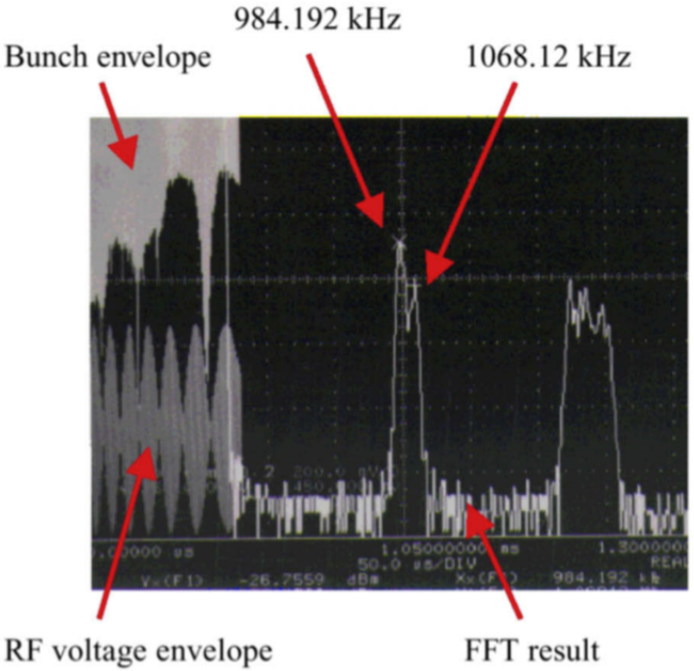


Cumulative fraction of normalized maximum voltage in rf bucket

Past experiment

Multi-bunch acceleration has already been demonstrated at PoP FFAG





In the experiment, two bunches were injected and accelerated and revolution frequencies of two bunches were measured as the indication of two bunch acceleration

In the experiment, only two bunch acceleration was carried out

Proposed experiment

- In the proposed experiment, single bunch injection with multibunch rf pattern is employed.
  ←in the present intensity of KURRI machine, no need to worry about space charge. Less systematic error caused by multiple signal input into monitor.
- Present goal is to demonstrate 10 bunch parallel acceleration
- The experiment proceeds as follows

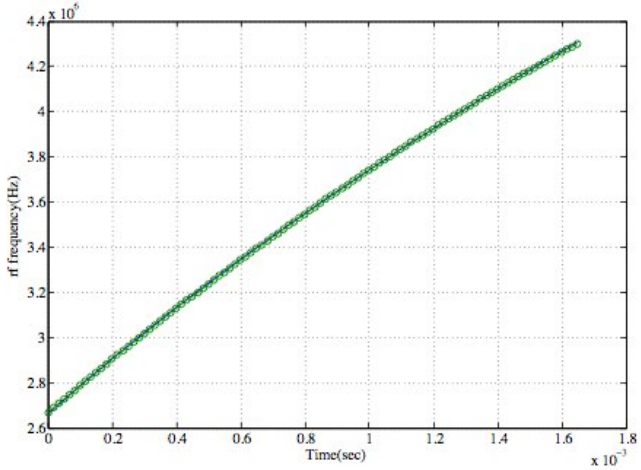
1. Single bunch rf acceleration with various rf voltages
2. Bunch separation dependence
3. Multi-bunch acceleration with unsaturated condition(up to 10 bunch)
4. Multi-bunch acceleration with saturated condition(fix bunch number varied rf voltage)

- Basically, bunch monitor is the main diagnostics.
  *Intensity measurement (beam loss pattern) is the key issue

Experiment: Step 1

low voltage, 1bunch

- Since available rf voltage is limited, in multi-bunch acceleration, rf voltage/ bunch is inevitably set low compared to the default acceleration voltage
- Therefore, data in low voltage acceleration with single bunch must be taken as a reference.
- The present goal is 10 bunch acceleration in maximum. (according to the rf voltage distribution, for 10 bunch case, peak voltage can be reduced to 70% of (nbunch*Vrf). So minimum examined voltage is ~15% of maximum available rf voltage. Beyond this, 20%, 25%, 30% is needed for the study of saturation effect)

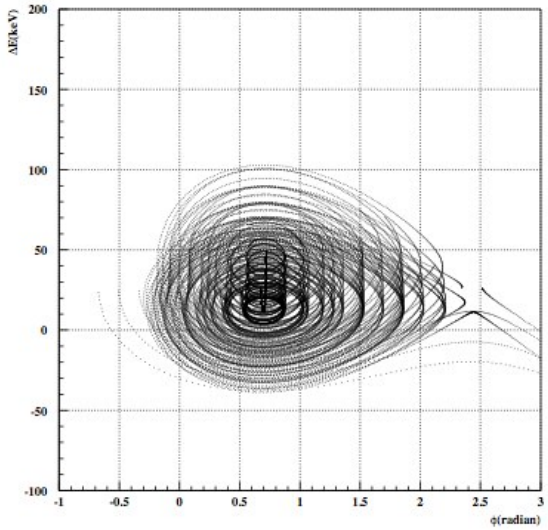


Typical rf pattern (KURRI booster, Vrf:2kV,Φ_s:40°

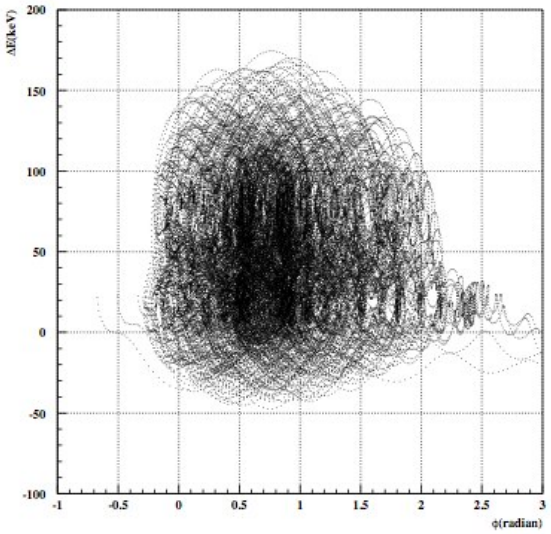
Experiment : Step 2

2bunch, bunch separation dependence

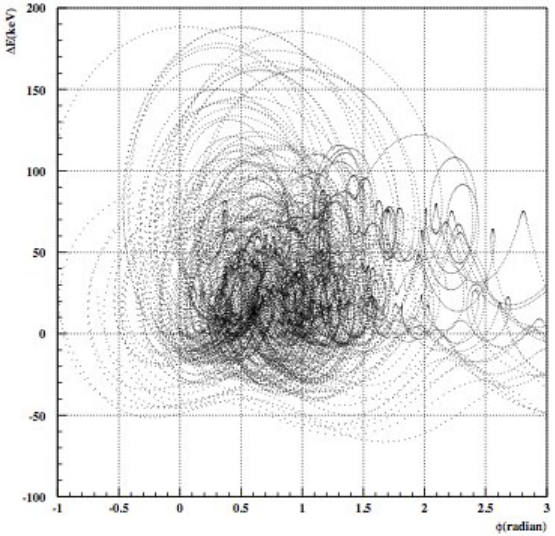
- In theory, maximum bucket height is ~$2v_s$. Thus, the frequency needs to be separated ~$4f_s$. As a confirmation and setting the lower limit of frequency separation, the frequency separation dependence needs to be studied.



1bunch



2bunch
bunch separation : 100μ sec
[Δf:120kHz]



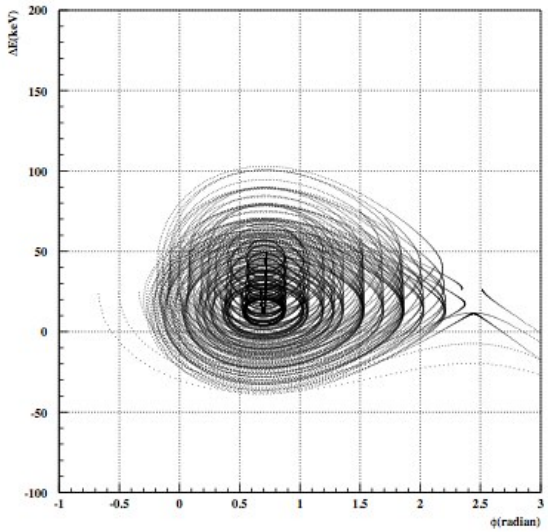
2bunch
bunch separation : 40μ sec
[Δf:50kHz]

In the simulation, the bucket collision observed ~70μsec (Δf:80kHz)
**Detailed study is still needed and ongoing for the understanding of longitudinal motion of multibunch acceleration

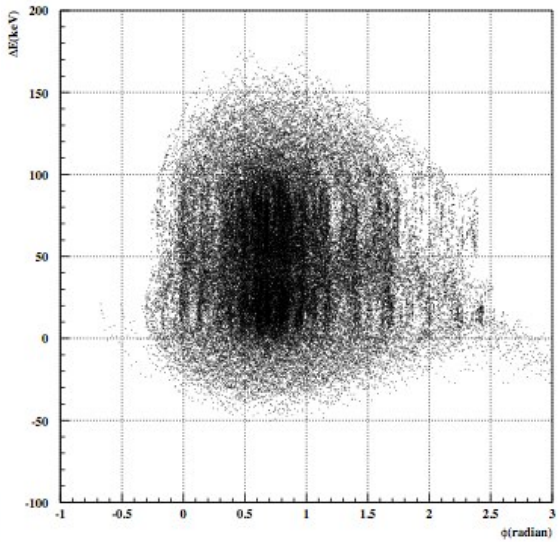
Experiment : Step 3

Mutibunch acceleration(unsaturated)

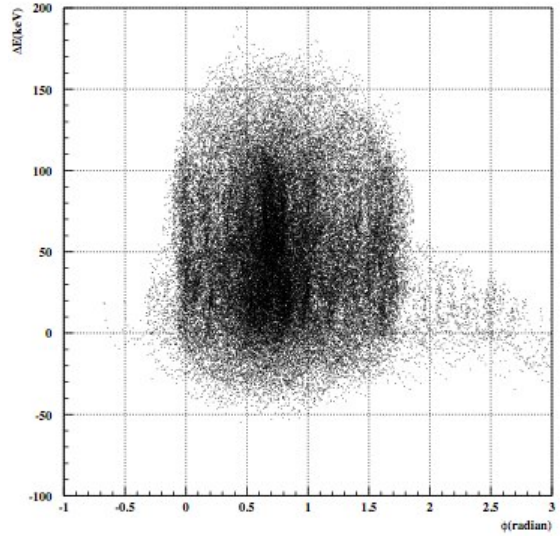
- With adding rf wave form, multibunch acceleration is tried(goal is 10-bunch acceleration at the moment)
- In the simulation, up to 15bunch parallel acceleration was examined. Basically, for all the cases, beam was surely accelerated to the final energy
  * In the 15-bunch acceleration, longitudinal acceptance slightly reduced.



1bunch



8 bunch
bunch separation : 188μ sec



15 bunch
bunch separation : 100μ sec

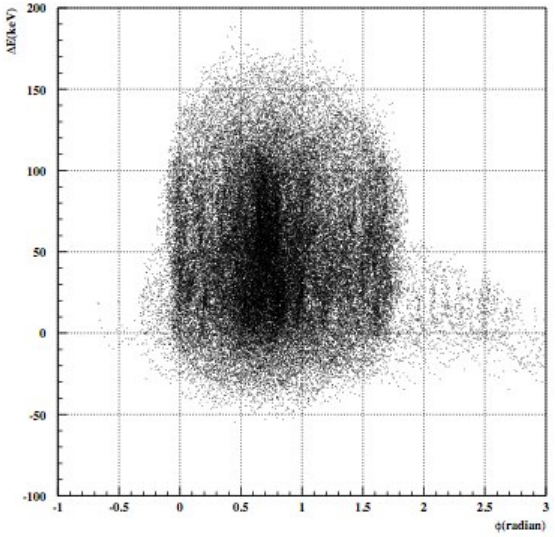
In the simulation, the bucket collision was observed at ~70μsec (Δf: 80kHz)

Experiment : Step 4

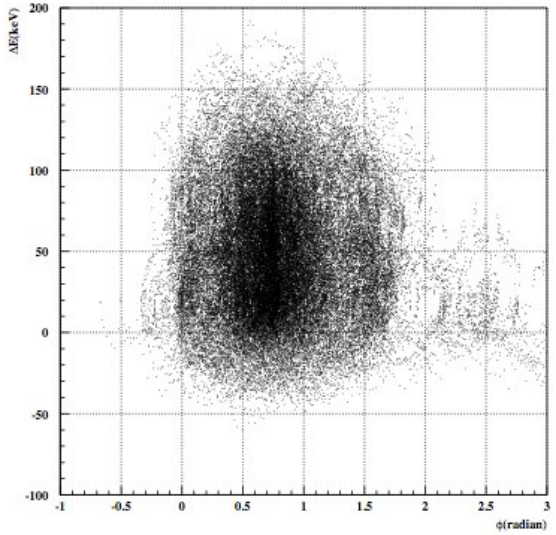
Multibunch acceleration(saturated)

- Fixing the number of bunch(ex 10-bunch and 5-bunch), introducing the rf voltage saturation, the influence of saturation is investigated.

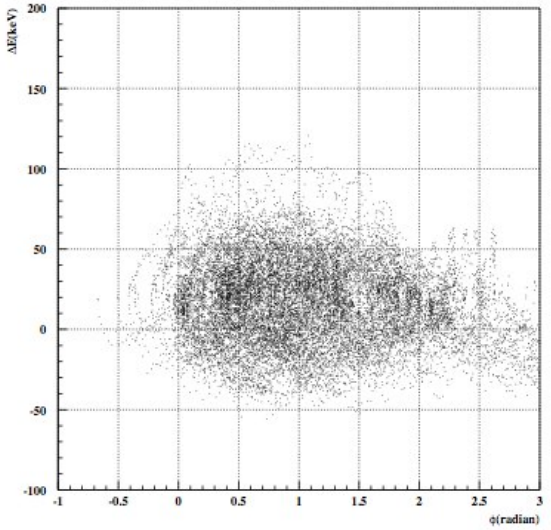
15bunch(bunch separation: 100μsec)



SF:1.0



SF:0.5



SF:0.3

$$SF \equiv \frac{V_{\max}}{V_{rf\,(1bunch)} \cdot n_{bunch}}$$

According to the simulation, rf voltage error of 5% over one cycle is tolerable.

Which machine should be used?

- At the moment, booster is employed as the model machine of beam simulation, but basically the experiment can be done using main ring

	Pros	Cons
Main ring	• Now, more intensive study is going on. • More flexible longitudinal phase space	Compared to booster, matching with simulation is worse.
Booster	• Better matching with simulation • Experiment can be done separately from main ring	

Things to know

- Machine availability
- Details of injection beam (bunch structure, energy spread)
- Details of rf cavity(maximum operation voltage etc)
- Details of function generator (in the manual, “ ’arbitrary’ analytical form can be generated.”) ➔whether it can generate the wave form of multi-bunch acceleration with one generator