Beam Stacking for High Intensity Pulsed Proton Beam with FFAG

Y. Ishi*

J.-B. Lagrange, T. Uesugi, Y. Kuriyama, Y. Mori,
Kyoto University Research Reactor Institute, Kumatori, Japan

Abstract

The reuirement of extremely high intensity pulsed proton beam with low spill rate has apeared from users in the field of spallation neutron source. To realize the beam satisfies this condition, beam stacking at extraction orbit in FFAG ring has been considered. Feasibility studies of rf stacking using the KURRI FFAG main ring are under consideration. Prior to these studies, beam simulations have been done.

INTRODUCTION

As a candidate of high intensity proton driver of spallation neutron source, potentially, an FFAG accelerator has advantage in terms of high repetition rate such as 100 - 1000 Hz. However, some users desire low spill rate ($\sim$10 Hz) for the experiments e.g. neutron radiography using TOF which needs to get rid of contamination from the pulse of different timing. FFAG rings can provide long interval pulse for users, while the machine operation itself is kept at high repetition rate by using rf stacking after acceleration[1]. This scheme reduces space charge effects at injection energy. For the machine, charge in each bunch can be reduced by high repetition rate. In the high energy region i.e. outer radius, accelerated beams are stacked and circulating around until necessary amount of charge is accumulated. For users, highly compressed beam with long time interval can be delivered. Schematic diagram of this methos is shown in Fig 1.
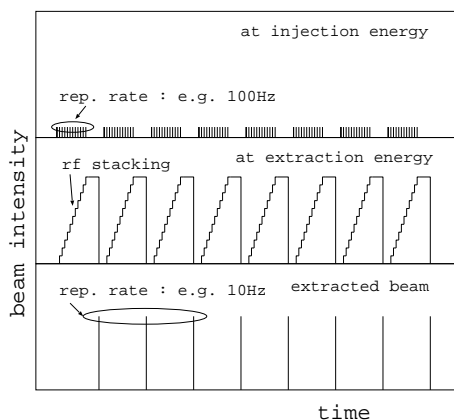

Figure 1: Schematic diagram of rf stacking at extraction energy

*ishi@.rri.kyoto-u.ac.jp

SIMULATION STUDIES OF RF STACKING

To confirm the feasibility of rf stacking at extraction energy, simulation studies have been carried out. The model machine used in this study simulates the KURRI FFAG main ring[2], in which the real beam studies are planned. The machine parameters are summarized in Tab 1.

Table 1: Machine parameters used in the simulations

field index k	7.7
kinetic energy T	11 - 150 [MeV]
momentum p	144 - 551 [MeV/c]
circumference C	28.8 - 33.6 [m]
momentum compaction factor α	0.115
rf voltage V_{rf}	8 [MV]
rf frequency f_{rf}	1.6 - 4.4 [MHz]
harmonic number h	1

rf acceleration scenario

Beam accelerations have been simulated according to the scenario shown in Fig 2, 3 and 4. In the real machine operation, we use similar scenarios in which synchronous phase ϕ_s and rf voltage are fixed at 30 degree and 4 kV respectively during all the acceleration period. On the other hand, in the scenario used in this simulation study, ϕ_s is dropped off linearly from 30 to zero degree when the energy of the beam is between 145 and 150 MeV for soft-landing. The rf voltage is also reduced in this region so that the bucket area A_B is constant in order to make momentum spread small at the end of acceleration. The bucket area is the phase-space area enclosed by the separatrix, i.e.

$$A_B = 16\sqrt{\frac{eV_{rf}}{2\pi\beta^2 E|h|\eta}}\alpha(\phi_s)\frac{\beta^2 E}{\omega_0}, \qquad (1)$$

where E is the total energy of the beam particle, η is the slippage factor, ω_0 is the revolution frequency and $\alpha(\phi_s)$ is the ratio of the bucket area to the stationary bucket. Here we use approximated expression of $\alpha(\phi_s)$, i.e.

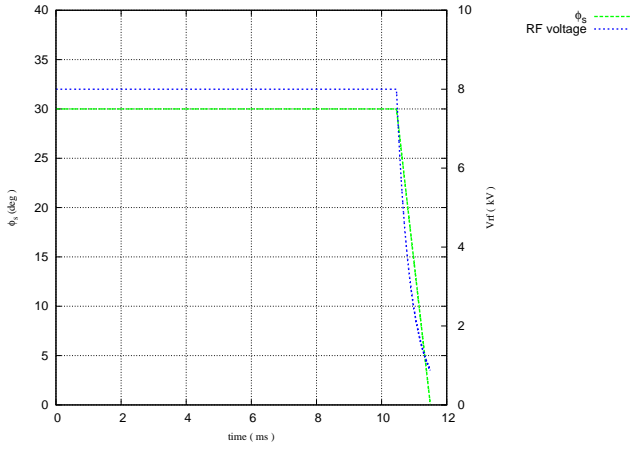$$\alpha(\phi_s) = \frac{1 - \sin(\phi_s)}{1 + \sin(\phi_s)}. \qquad (2)$$

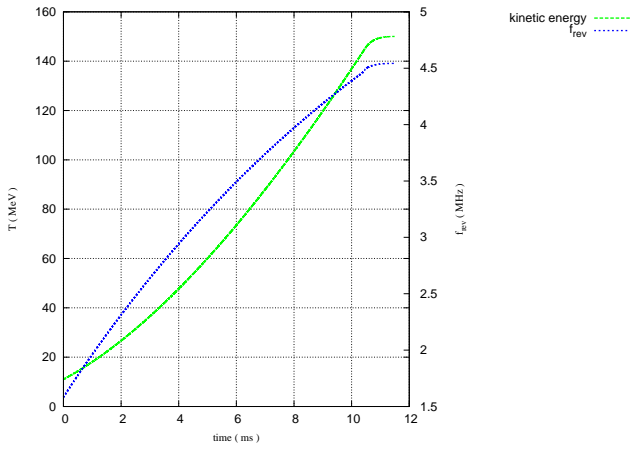Figure 2: Acceleration scenario for the rf voltage and the synchronous phase

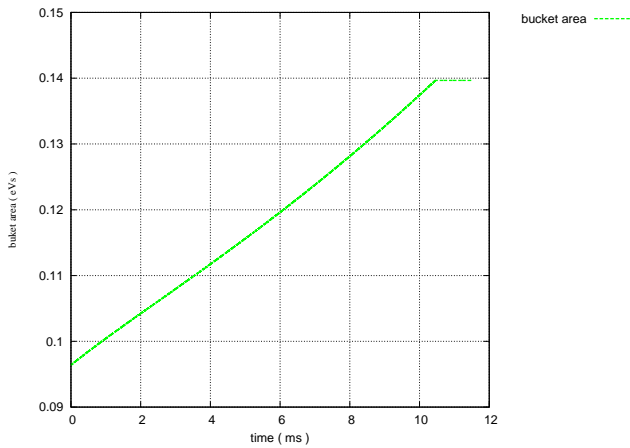Figure 3: Acceleration scenario for the kinetic energy and revolution frequency

Figure 4: Acceleration scenario for the bucket area

beam stacking simulation

For the beam stacking simulation, we used longitudinal 2-d tracking code which solves the following difference

equations,

$$W_{n+1} = W_n + \frac{eV}{\omega_0}(\sin\phi_n - \sin\phi_s) \qquad (3)$$

$$\phi_{n+1} = \phi_n + \frac{2\pi h\eta\omega_0}{\beta^2 E}W_{n+1}, \qquad (4)$$

where $W = \Delta E/\omega_0$, ΔE is the total energy difference from the synchronous particle and n is incrementing at each rf period. In this mapping, the symplectic condition is satisfied.

Stacking processes are simulated using 1 000 test particles for each acceleration batch. Adding the acceleration batch, circulating particles are accumulated in the virtual ring Therefore, 10 000 test particles are tracked in the final batch.

a:The end of first batch of acceleration

b:The end of second batch of acceleration

c:The end of 5th batch of acceleration
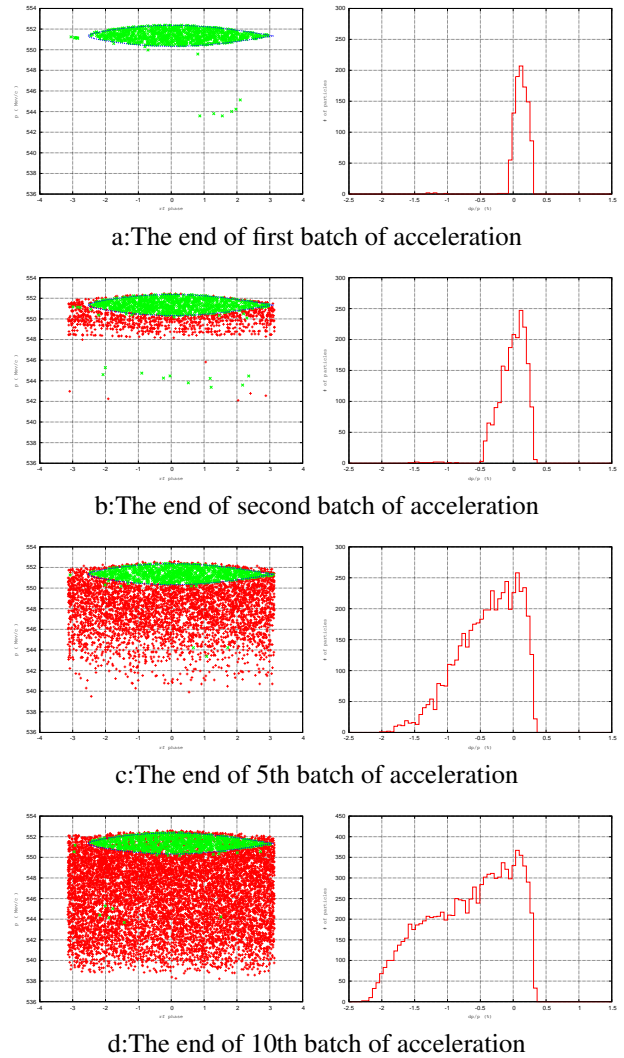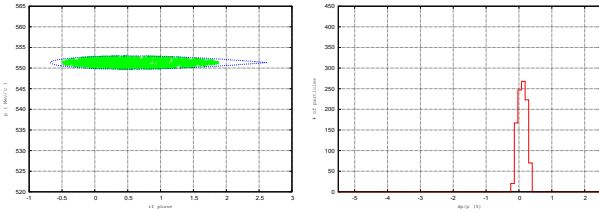

d:The end of 10th batch of acceleration

Figure 5: Phase space plots from the stacking simulations with soft-landing

Figure 5 shows the results from the stacking simulations. In the left column, plots of phase space structure are shown. In each plot the vertical axis is the momentum and horizontal one is the rf phase. The red points are stacked particle

coasting around the extraction orbit, the green ones are accelerated particles landing on the extraction orbit and the blue lines are separatrices. In these simulations, the acceleration goes up to 150 MeV. While the landing process is going on, already stacked particles are slipping below the bucket in the phase space. Eventually, beams have been stacked below the extraction momentum. In the right column, momentum distributions are plotted. After first acceleration, full width of momentum spread is about 0.5%, the final momentum spread after 10 stacks is 2.5% of full width. This is much smaller then naive guess that is intrinsic momentum spread of each stacked beam multiplied by number of stacks i.e. $0.5 \% \times 10$.
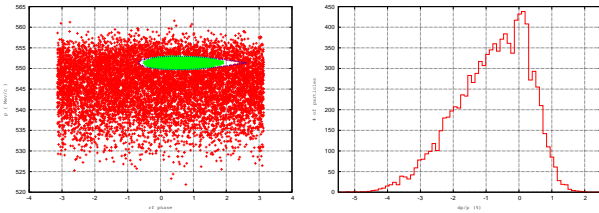
To see the effect of soft-landing, we tried to simulate stacking with the scenario in which ϕ_s is fixed to the final energy. Figure 6 shows the similar plots as Fig 5. The final momentum spread is about two times larger than the one with soft-landing process.

a:The end of first batch of acceleration
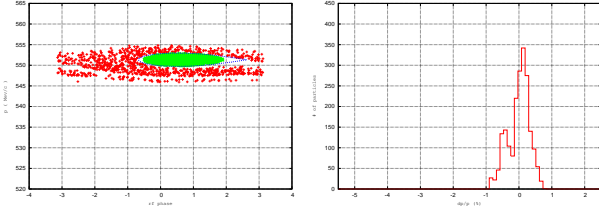
b:The end of second batch of acceleration

c:The end of 10 th batch of acceleration

Figure 6: Results from stacking simulations without soft-landing

perturbation of acceleration bucket to the stacked beam

It is necessary to check if the acceleration bucket affects the stacked beams coasting around the extraction orbit. Zero emittance test beam whose kinetic energy is 100 MeV are generated with $\Delta p/p = 0$ and uniformly distributed in the rf phase. Then they are mapped by solving the difference equations, watching if momentum spread is blowing up, while the accelerating bucket is coming up. This tracking is applied for three cases:

1. $V_{rf} = 4$ kV, $\phi_s = 30$ degree;

2. $V_{rf} = 8$ kV, $\phi_s = 30$ degree;

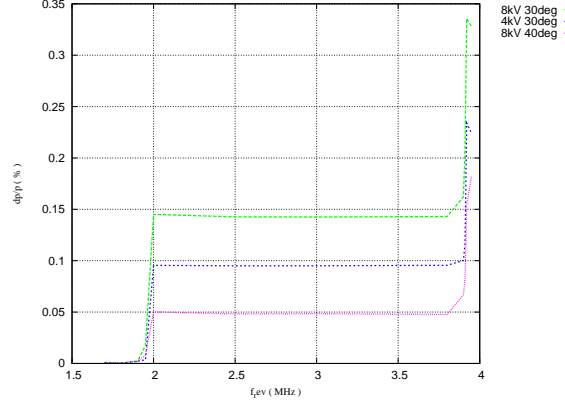3. $V_{rf} = 8$ kV, $\phi_s = 40$ degree.

Figure 7: Perturbation by the accelerating bucket.

The results are shown in Fig 7. The vertical axis is the momentum spread of the beam, and the horizontal axis is the drive frequency. There are two steps around 2 MHz and 4 MHz in each case. The second step around 4 MHz is direct disturbance of the bucket. But the first step around 2 MHz can be evidence that coasting beam can be affected when the accelerating bucket is passing through the frequency which is half of revolution frequency of the coasting beam. Fortunately, the amount of the effect is small. In these plots, it is clear that higher rf voltage makes larger perturbation compering case 1 and case 2. From case 2 and case 3, one can imagine that slower acceleration makes larger perturbation.

discussion

From the simulation studies, followings are ascertained:

- Final momentum spread is about 2.5 % in full width.

- To reduce final momentum spread, soft-landing pattern is essential.

- According to Fig 4, soft-landing should be started earlier for small momentum spread, but for the high repetition rate.

- There are small but significant effects of perturbation in circulating beam by the accelerating bucket when the drive frequency is the half of the revolution frequency of the stacked beam.

SUMMARY

To increase beam intensity keeping low spill rate, rf stacking at extraction energy has been investigated. Prior to beam experiments, simulation studies have been carried out. Since final momentum spread is quite large, acceleration pattern should be optimized to keep longitudinal emittance small.

REFERENCES

[1] S. Machida ,"RF stacking at extraction momentum" *FFAG Workshop 2003,October 13-17, 2003 at BNL*, http://www.cap.bnl.gov/mumu/conf/ffag-031013/Machida2.pdf.

[2] Y. Ishi ,"Present Status and Future of FFAGs at KURRI and the First ADSR Experiment" *Proc. IPAC'10, Kyoto, Japan*,