SIMULATION OF RF STACKING COMBINED WITH COOLING EFFECTS

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Abstract

The Radioactive Isotope Beam Factory is being proposed at RIKEN, which consists of a Superconductive Ring Cyclotron (SRC) and a complex of Accumulator Cooler Ring (ACR), Booster Synchrotron Ring (BSR) and Double Storage Ring collider (DSR). This Multi-Use Experimental Storage Rings (MUSES) will be constructed for the production of high flux RI beams and the experiments of nuclear physics and related science. This paper concentrated on the RF stacking method combined with cooling effects that will be used for accumulating radioactive beams (with transverse emittance 5π.mm.mrad and Δp/p=±0.5%) extracted from SRC into ACR. The procedure of RF stacking was simulated. The cooling effect, in which the coupling effect of longitudinal cooling and transverse cooling was considered, was taken into the simulation. The possibility of this method to be used in beam accumulation of ACR was discussed.

1. INTRODUCTION

The main purpose of ACR is to prepare high intensity, high quality cooled beam for DSR. So the injection system will be designed to inject as many particles as possible into ACR acceptance. A combination of multiturn injection and RF stacking methods will be applied to ACR. The beam from SRC or RIB from the target is multiturn injected into the transverse acceptance while the instant offsets of closed orbit are formed by kickers, and then captured by RF field into the longitudinal acceptance. Another important point is that cooling method takes effect simultaneously during injection, and it will enlarge the possibility of the beam intensity.

In this paper RF stacking procedure was simulated for typical nuclear beam $^{132}Sn^{50+}$, the parameters are listed in Table 1, the momentum spread and transverse emittance are for the beam after target, the phase spread of the beam is that at injection point. The RF stacking system stacks beam in longitudinal (energy) phase space by using of RF system and both electron cooling and stochastic cooling systems.

The main parameters of accumulator ring (ACR) are listed in Table 2.

The repetitive RF stacking procedure consists of following three steps:

1. Capture:

The RF voltage is put on and the beam is captured in the stationary bucket. After 1/4 period of synchrotron oscillation in the phase space the RF voltage is reduced to accelerating voltage and keep the beam in the bucket. By this way the momentum spread of the injecting beam is reduced and the phase space dilution factor in longitudinal phase space will be reduced;

2. Acceleration:(or Deceleration)

The RF voltage, frequency, and synchronous phase are adiabatically changed and the beam is moved to the top of the stacking orbit. During this step the momentum of the injected beam is changed and the closed orbit is changed. This makes the stacked beam clear off the injection orbit for the next single-turn or multiturn injection;

3. Deposit:

The RF voltage is switched off and the beam is released from accelerating bucket and remained on the stacking orbit.

Table 1. Parameters of Typical Nuclei Beams

Typical Beams	$^{132}Sn^{50+}$
Kinetic Energy, T(MeV/u)	210
γ	1.225
β	0.578
cp(MeV/u)	659.8
Revolution Frequency, f(MHz)	0.97
Harmonic Number of ACR, h	30
RF Frequency of ACR, f(MHz)	29.1
Momentum Spread after Target	±0.5%
Phase Spread (degree)	±10°
Transverse Emittance(π.mm.mrad)	5
Momentum Difference at Injection	-1%
Momentum Difference at Stack top	2.7%

Table 2. Parameters of Accumulator Cooler Ring

Circumference C(m)	168.484
Average Radius R(m)	26.82
Max. Magnetic Rigidity of Beam(T.m)	7.244
Max. Dipole Magnetic Field B(Tesla)	1.5
Radius of Curvature ρ(m)	4.829
Betatron Tune Qx/Qy	4.555/3.54
Max. Betatron Amplitude, βx/βy(m)	18.3/24.5
Betatron Amplitude at Injection Point	4.24/8.75
Phase Advance between Two Bumpers	π
Betatron Amplitude at Exit of Septum	1.06
Dispersion at Injection Point, Dx/Dy(m)	4.518/0
Transition gamma, γ_{tr}	4.987

For every acceleration the bucket passes over the stacked particles and disturbs them. The main effect is that the particles move away from the stacking top to the bottom. The disturbation quantity of bucket passing the stacked beam is the same as the height of the stationary bucket height at stacking top. Finally the particles filled into the energy acceptance.

During the whole procedure electron cooling and (or) stochastic cooling are (is) applied at the stacking top. If the beam has a long lifetime we can expect a large beam intensity, limited by the space charge effect.

2. RF STACKING COMBINED WITH STOCHASTIC COOLING

The differential equations for the simulation of RF stacking procedure combined with stochastic cooling are;

$$\frac{\mathrm{d}\Delta \mathrm{p}}{\mathrm{d}t} = \frac{eV_{\mathrm{RF}}}{2\pi R_s}(\sin\Phi - \sin\Phi_s) + \text{Stochastic cooling term}$$
$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -\frac{1}{2\pi}\cdot\frac{h\eta\omega_s}{R_s P_s}\frac{\Delta p}{2\pi R_s} \qquad (1)$$

where the stochastic cooling term was derived according to reference[1]. The stochastic cooling force is larger for less particle number, bigger momentum deviation and larger charge to mass ratio. So stochastic cooling can efficiently compensate the momentum shift and spread induced by bucket scanning during the stacking procedure.

During the simulation, the RF stacking procedures of typical ion beam $^{132}Sn^{50+}$ are studied. The beam in simulation has a Gaussian initial distribution. The parameters of stochastic cooling system are listed in Table 3. These parameters are constant during the simulation, so as to make the simulation easier. The simulation results can be seen in Figures 1 and 2, the parameters used are listed in Tables 4 and 5, respectively.

From the results one can find that the key point to keep the stacked beam inside the stacking region is the accelerating voltage (when the cooling system is the same), or the bucket height of the RF system near the top of the RF stacking region. If that voltage or bucket height is small enough, good distribution can be achieved for given initial momentum spread, in sacrifice of stacking efficiency. So it is better to optimize the initial momentum spread of the injection beam by debuncher. The debuncher at the transport line from the target point to the injection point of ACR can reduce the RF voltage needed for capturing the beam and make it easier to design the RF cavity.

Table 3. Parameter of Stochastic Cooling

Number of Particles	1E7
Kicker Efficiency	0.5
Total Temperature(K)	400
Midband Frequency (GHz)	0.75
Frequency Width(GHz)	0.5
$Z_P/Z_C(\Omega)$	25/50
Number of Pickups	10
Output Power(kW)	10

Table 4. Parameter of RF stacking for $^{132}Sn^{50+}$ in Figure 1

Injection cp(MeV)	659.8
Injection ΔP/P(%)	±0.5
Stacking Top cp(MeV)	683.6
Stacking Top ΔP/P (%)	±0.04
Capture Voltage(kV)	600
RF Oscillation Period(μs)	21.9
Accelerating Voltage(kV)	5
Accelerating Phase(deg)	16
RF Oscillation Period(μs)	240
Stacking Period(ms)	30
Stacking Periods	100
RF Stacking Efficiency(%)	72

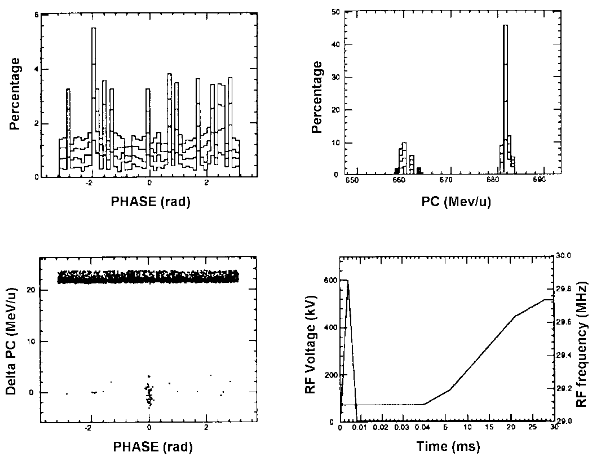

Fig.1. Simulation result of RF stacking for $^{132}Sn^{50+}$

Table 5. Parameter of RF stacking for $^{132}Sn^{50+}$ in Figure 2

Injection cp(MeV)	659.8
Injection ΔP/P(%)	±0.5
Stacking Top cp(MeV)	683.6
Stacking Top ΔP/P (%)	±0.06
Capture Voltage(kV)	600
RF Oscillation Period(μs)	21.9
Accelerating Voltage(kV)	10
Accelerating Phase(deg)	8
RF Oscillation Period(μs)	170
Stacking Period(ms)	30
Stacking Periods	100
RF Stacking Efficiency(%)	76

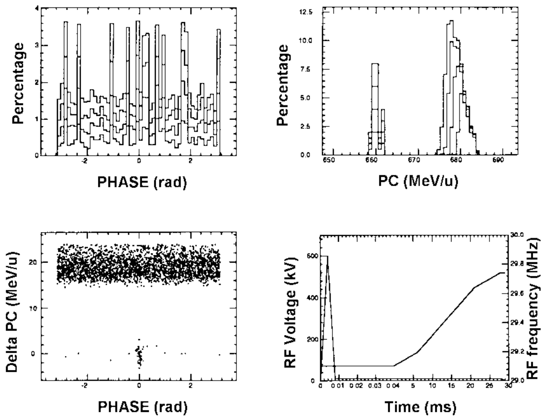

Fig.2. Simulation of RF stacking for $^{132}Sn^{50+}$

3. RF STACKING COMBINED WITH ELECTRON COOLING

The following differential equations describe the physical method of stacking with electron cooling.

$$\frac{d\Delta p}{dt}=\frac{eV_{RF}}{2\pi R_s}(\sin\Phi-\sin\Phi_s)-k\frac{\Delta p}{\left(\theta^2+\Delta p_{rel}{}^2\right)^{3/2}}\left(2L_{FH}+\frac{3\theta^2}{\left(\theta^2+\Delta p_{rel}{}^2\right)}L_{MH}\right) \quad (2)$$

$$\frac{d\Phi}{dt}=-\frac{1}{2\pi}\cdot\frac{h\eta\omega_s}{R_s P_s}\frac{\Delta p}{2\pi R_s}$$

$$\frac{d\theta}{dt}=-k\frac{\theta}{\left(\theta^2+\Delta p_{rel}{}^2\right)^{3/2}}\left(2L_{FH}+\frac{\theta^2-2\Delta p_{rel}{}^2}{\left(\theta^2+\Delta p_{rel}{}^2\right)}L_{MH}\right)$$

where $L_{FH,}L_{MH}$ are constant, $\Delta p(t)$ is momentum difference, $\Phi(t)$ is the phase of particle reference to RF field, $\theta(t)=\sqrt{\varepsilon_{x,y}/\beta_{x,y}}$, $\Delta p_{rel}(t)=\Delta p(t)/(\gamma p_s)$, and $k=2\pi r_e r_n j_e Z^2/e\beta^4\gamma^5 A$.

One can see clearly that the electron cooling force is larger for smaller momentum deviation and larger charge to mass ratio. So electron cooling can compensate the momentum shift induced by bucket scanning during the stacking procedure at small momentum spread (near the stacking top). If the cooling force cannot compensate the increase of the momentum spread at the stacking top, the beam will be lost during the procedure of the RF stacking.

The simulation result can be seen in Figure 3 and the parameters used are same as in Table 4 but for the stacking efficiency is 70%.

4. RF STACKING COMBINED WITH BOTH COOLING METHODS

As described above, the stochastic cooling system is efficient for particle with larger momentum deviation and the electron cooling system is efficient for particle with small momentum deviation, so when both methods are taken into account, one can expect better results than that when only one method is used.

The simulation result considering both cooling mechanisms can be seen in Figure 4, using parameters in Table 4, the stacking efficiency is 80%, and the efficiency will not change when more than 100 periods of RF stacking is done.

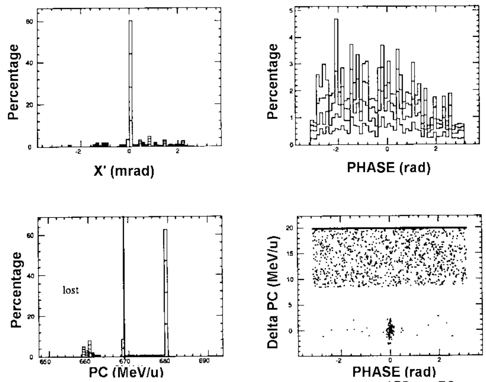

Fig.3. Simulation of RF stacking for $^{132}Sn^{50+}$ with electron cooling

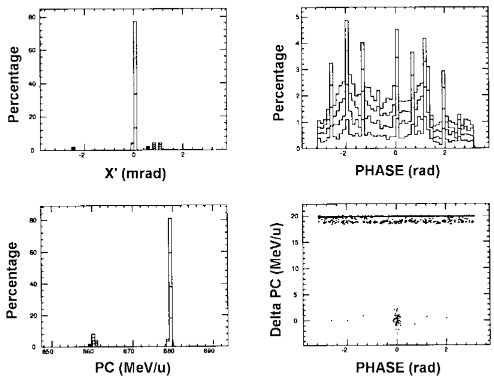

Fig.4. Simulation of RF stacking for $^{132}Sn^{50+}$ with electron cooling and stochastic cooling

5. SUMMARY

Simulations of RF stacking with cooling systems are done using a self-developed code verified by the experimental results of TARN II[2,3]. The property of the RF cavity (600kV) used here is difficult to obtain. It's possible to be reduced by pre-debunch system at the beam line. If multiturn injection method is used simultaneously, the momentum compression by RF cavity may not work well, because beam is already debunched in the ring during the multiturn injection.

REFERENCES

[1] D.A.Goldenberg, et al., `Behavior of Power-Limited Transverse Stochastic Cooling System', LBL-24979.
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[3] Y. J. Yuan, et al., `Simulation of RF Stacking and Single-Turn Injection and Multiturn Injection', Proc. 14th Int. Conf. on Cycl. and Their Appl., South Africa, Oct. 1995.