SIMULATION STUDY OF BEAM ACCUMULATION WITH MOVING BARRIER BUCKETS AND ELECTRON COOLING

T. Katayama, C. Dimopoulou, B. Franzke, M. Steck, GSI, Darmstadt, Germany

D. Moehl, CERN, Geneva, Switzerland

T. Kikuchi, Utsunomiya University, Utsunomiya, Japan

Abstract

An effective ion beam accumulation method for the NESR of the FAIR project, is investigated numerically. The principle of the proposed accumulation method is as follows. The ion beam bunch from the Collector Ring is injected in the longitudinal gap prepared by two moving barrier pulses. The injected beam becomes coasting after switching off the barrier voltages and merges with the previously stacked beam. After the momentum spread is well cooled by electron cooling, the barrier voltages are switched on and moved away from each other to prepare the empty space for the next beam injection. This process is repeated to attain the required intensity. We have investigated this stacking process numerically, including Intra Beam Scattering which limits the momentum spread of the stacked beam and hence the stacked particle number in the ring. Calculated results are compared with experimental data from the ESR where a proof of principle experiment of the proposed method was performed. This experiment is described in a companion paper at the present workshop.

INTRODUCTION

The Barrier Bucket (BB) method is a new way of beam manipulation in longitudinal phase space in synchrotrons and storage rings. One important application of the BB method is a beam injection and accumulation into a storage ring with simultaneous use of beam cooling. As an example, we reported a feasibility study of 3 GeV antiproton beam accumulation in a storage ring with use of BB operation and stochastic cooling in the last workshop [1].

In the present paper, we study a scheme of BB operation for the injection and accumulation of rare isotope beams, typically $^{132}Sn^{50+}$ ions, into the storage ring, NESR (New Experimental Storage Ring), which is conceived as a key experimental ring for the FAIR project at GSI [2].

In the scenario of FAIR, a beam of radioactive nuclei is produced through the nuclear reaction of projectile fragmentation of a high energy heavy ion beam with a target nucleus. Among the many kinds of unstable nuclei produced, the required nuclei beam is selected in the fragment separator and is injected into the Collector Ring (CR). In the CR, momentum spread and transverse emittances of the rare isotope beam are cooled down with stochastic cooling. The cooling time in the CR is a key limitation of repetition time for the injection into the NESR. For the $^{132}Sn^{50+}$ beam with 10^8 ions, and an initial relative momentum spread of 10^{-3} (2σ), the e-folding cooling time is estimated at around 2 sec. The pre-cooled rare isotope beam in the CR is re-bunched with RF field of harmonic number h=1, and is fast extracted. If necessary the beam will be decelerated to 100 MeV/u in another storage ring RESR before injection into the NESR.

The accumulated rare isotope beam in NESR will be used for experiments with an internal target or for head on collision experiments with an electron beam or antiproton beam. To achieve high intensity of the rare isotope beam in the NESR in order to realize a sufficient luminosity, a short cycle time and a highly efficient beam accumulation method is required.

In the present paper, a BB method assisted by electron cooling for stacking of the rare isotope beam is investigated from the point of view of beam dynamics and simulation results are presented. The calculated results are compared with experimental data from the ESR where a proof of principle experiment was performed to verify the accumulation method of the present scenario [3].

OPERATION OF BEAM STACKING

Typical beam parameters of the $^{132}Sn^{50+}$ beam from the Collector Ring are tabulated in Table 1.

Table 1: Beam parameters of $^{132}Sn^{50+}$

Beam energy	740 MeV/u
Number of ions	10^8/batch
Momentum spread at coasting (2σ)	0.05%
Beam duration	400 nsec
Energy spread	±0.6 MeV/u
Transverse emittance (H&V)	0.5π·mm·mrad

Several operation schemes of BB stacking are conceivable, e.g. use of a fixed barrier pulse instead of moving barriers, or use of half wavelength barrier pulses instead of full wave length ones. However we believe that the scheme studied here is the most appropriate option. The operation of the barrier pulses during the first Injection

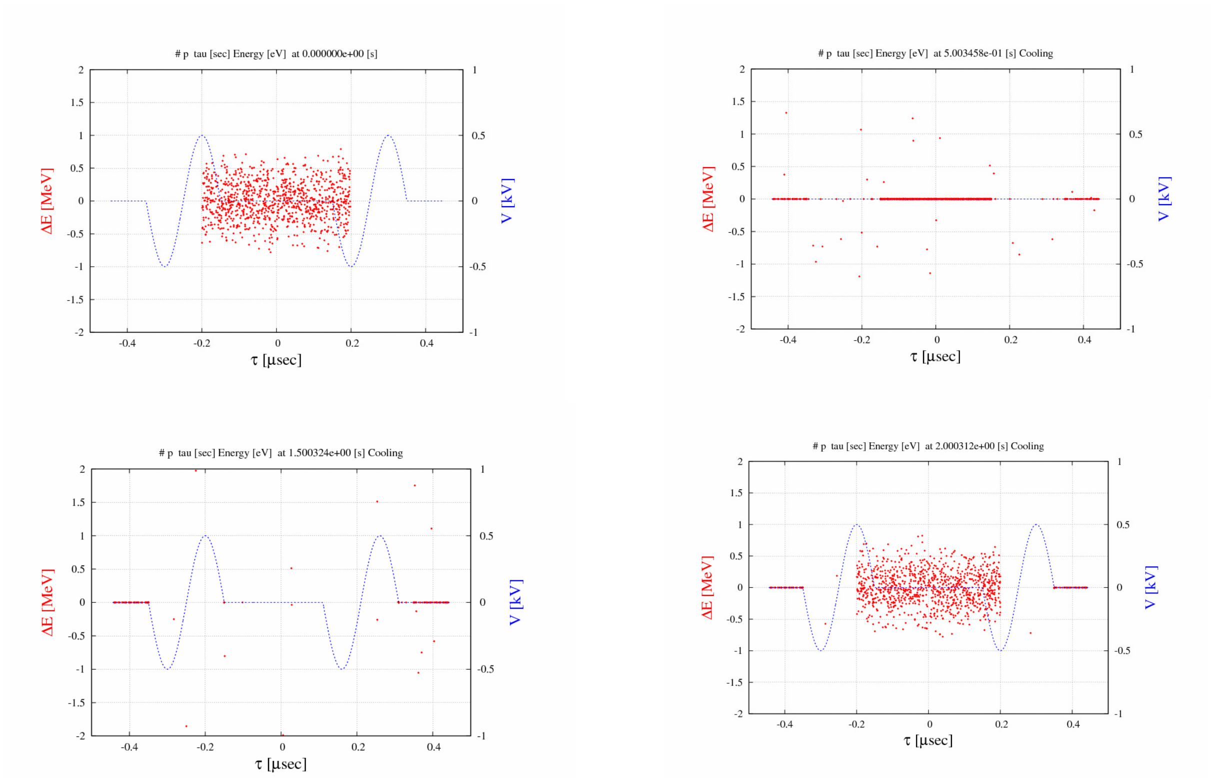

Figure 1: Barrier pulses (blue color) and particle mapping (red points) in the longitudinal phase space. From top left to bottom right, t=0 sec (1st Injection), t=0.5 sec (Cooling), t=1.5 sec (Compression) and t=2.0 sec (2nd injection).

cycle is illustrated in Fig 1. At t=0.0 sec, beam is injected into the 400 nsec gap between the two barriers (Injection). The barrier voltages are gradually decreased and switched off so that the beam becomes coasting (Debunching). At t=1.6 sec the beam is well cooled (Cooling). Then the two BB pulses are switched on next to each other, and moved apart to open the gap for the next beam injection. The previously injected beam is compressed and cooled in the stacked area (Compression). In this example the RF voltage is 500 Volt. At t=2.0 sec, the new batch is injected.

ALGORITHM AND EQUATIONS FOR SIMULATION

Phase Equations

Equations of motion in the longitudinal phase space governed by the barrier bucket voltages are given by

$$\frac{d\tau}{dt} = -\frac{\eta \Delta E}{\beta^2 E_0}, \quad \frac{d(\Delta E)}{dt} = \frac{\varepsilon e V(\tau)}{T_0} \tag{1}$$

where η is the slip factor of the ring, β the relativistic factor, E_0 the total energy per nucleon of synchronous particle, ΔE the energy deviation from synchronous energy, V the BB pulse voltage. $\varepsilon = Q/A$ is the charge to mass ratio of the ion and T_0 the revolution period in the ring.

Here the canonical variables are τ and ΔE. Note that in the present paper all the values related with energy or momentum are given as the value per nucleon. Separatrix height, namely the maximum deviation of energy in the stable region, is given as

$$\Delta E_b = \left(\frac{2\beta^2 E_0 \varepsilon e V_0 T_1}{\pi |\eta| T_0} \right)^{1/2} \tag{2}$$

where a barrier voltage of *sin* shape with one full wave length and an amplitude V_0 is assumed. T_1 is the duration of the barrier pulse. It is clear from this formula that the small momentum spread obtained by electron cooling will have a benefit of needing only a low barrier voltage to confine a cooled beam in the stable phase area.

Drag Force of Electron Cooling

Strong electron cooling is a key factor of this scenario. To calculate the cooling drag force, among several formulae, we employ the Parkhomchuk empirical formula [4] which is represented in the laboratory frame as follows. Here ΔE is a energy difference and ε the transverse emittance.

$$\frac{d(\Delta E)}{dt} = -\Delta E \cdot k \cdot G, \quad \frac{d\varepsilon}{dt} = -\varepsilon \cdot 2k \cdot G$$

$$G = \frac{1}{\left[\beta^2\gamma^2\varepsilon/\beta_c + (\Delta E/\beta E_s)^2 + 2T_{e,eff}/m_e c^2\right]^{3/2}}$$

$$k = \frac{4 r_e r_n c n_e \eta_c L_p}{\gamma^2} \cdot \frac{Z^2}{A} \tag{3}$$

where β and γ are relativistic factors, β_c the betafunction at the cooler section, $T_{e,eff}$ the effective energy spread of electron beam, r_e and r_n are classical electron and nucleon radius, respectively, η_c the ratio of length of electron cooler and ring circumference. The effective electron temperature reflects the quality of the electron cooler and the recent electron cooler has a number of around 10^{-4} eV. The Coulomb logarithm is given as 2.0 for the NESR electron cooler.

Intra Beam Scattering Effects

When one accumulates a large number of ions of low energy and high charge state in the storage ring, the cooled momentum spread and transverse emittances are limited by Intra Beam Scattering. In the present study we calculated the IBS heating rates with use of Martini analytical formula [5] where particle distribution functions are assumed as Gaussian and IBS rates are calculated with use of rms values of momentum spread and transverse emittances. In the present particle tracking, sigma values of $\Delta p/p$ and transverse emittances are derived from 6D phase points of injected and accumulated particles. IBS heating rates are functions of Twiss parameters of the ring and then they are calculated at each element of the ring and are averaged along the ring circumference.

With use of the calculated IBS heating rates, in the present simulation study, each particle receives a random kick proportional to the heating rate at each computing cycle.

COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS AT ESR

In order to check the validity of the present stacking scheme we have performed a stacking experiment at ESR [3]. In the following experimental parameters related to the BB operation are compiled.

The circumference of ESR is 108.36 m and the revolution time of the 65 MeV/u $^{40}Ar^{18+}$ ion beam is close to 1.0 μsec. The measured relative momentum spread of the injected beam from SIS-18 is 10^{-3}, defined as 2σ with the Gaussian distribution. The bunch length of injected beam is about 200 nsec, containing $7\cdot10^7$ ions.

Table 2: ESR experimental parameters

Beam energy	65.3 MeV/u
Number of ions	$7\cdot10^7$/batch
Relative momentum spread at coasting beam(2σ)	0.1%
Bunch duration at injection	200 nsec
Transverse emittance	0.5 π·mm·mrad
Effective cooler length	1.8 m
Beta functions at cooler H/V(Dispersion=0)	16 m/6.88 m
Electron beam current	100–500 mA
Electron beam diameter	5 cm
Magnetic field	0.04 T
Effective electron energy spread $T_{eff,e}$	10^{-3} eV
Maxmal BB Pulse voltage	±170 V
BB Pulse width (*sin* shape)	200 ns (5 MHz)
Adiabatic switch ON of BB	0.5 sec
BB pulse movement speed	0.5 sec
BB voltage decreasing time	10^{-6} sec

Evolution of Electron Cooling and Equilibrium Values

A typical example of the calculated evolution of momentum spread and transverse emittances is illustrated in Fig. 2. The full cooling time down to equilibrium is around 7 sec, and the equilibrium values are determined by the balance of IBS heating and electron cooling.

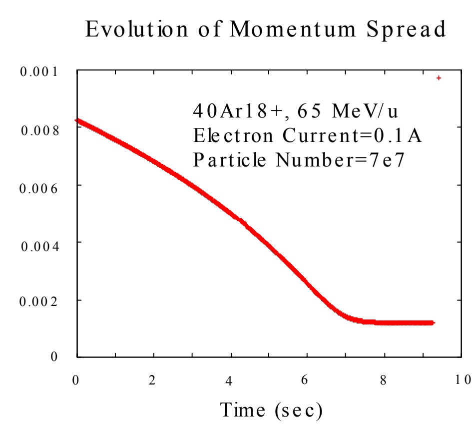

Figure 2 (a): Calculated evolution of momentum spread of the 65 MeV/u $^{40}Ar^{18+}$ beam at ESR. Electron current is 0.1 A and particle number is $7\cdot10^7$.

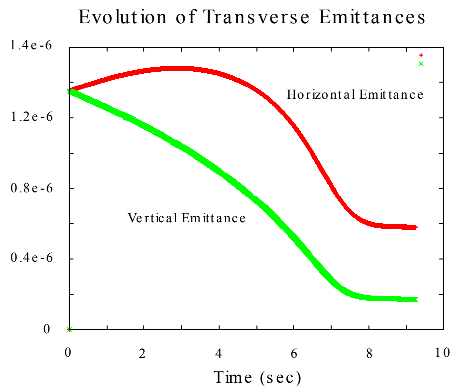

Figure 2 (b): Calculated evolution of transverse emittances. Electron current is 0.1 A and particle number is $7 \cdot 10^7$.

The calculated and measured equilibrium values are given in Fig. 3 as a function of the number of ions. In the figure blue squares show the calculated results and red circles the measured ones. For the horizontal emittance both are quite well in agreement while for the momentum spread the calculated ones are around a factor of 2 larger than the experimental results.

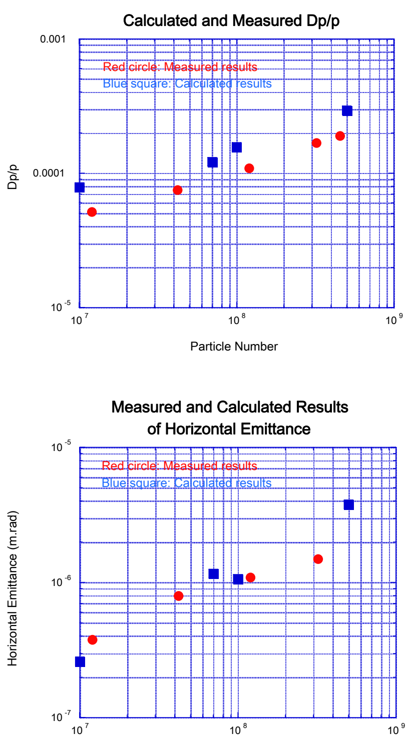

Figure 3: Equilibrium values of momentum spread (top) and horizontal emittance (bottom). Electron current is 0.1 A. Blue squares represent the calculated results and red circle the measured ones.

Stacking Simulation & Experiments

We calculated the stacking process for the ESR parameters and compared them with the experimental results. Typical results of stacking simulations are given in Fig. 4 where accumulated particle number and stacking efficiency are given as a function of time. The cycle time is set as 5 second. The stacking efficiency is around 60 % which has to be compared with the measured results of around 70 %.

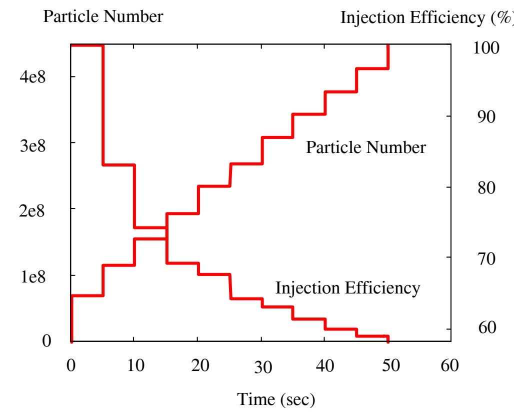

Figure 4: Calculated particle number and stacking efficiency as a function of time. Cycle time is 5 sec, electron current is 0.1 A and the barrier voltage is 120 Volt.

In the experiment the electron current were set at 0.1 A and 0.2 A, and the barrier voltage was 120 Volt. The stacking efficiency gradually decreased during 8 times injection, and the stacking efficiency was around 70 % after the 8th injection. A visible difference of stacking efficiency was not observed for the two electron currents. The primary reason of particle loss is as follows. Accumulated particles that fall into the pulsing time of the injection kicker will be aborted. This happens to particles which are not sufficiently fast moved into the stacking area or if the kicker pulse is misfired or too long. The second reason for losses is that the momentum spread of particles becomes larger than the ring acceptance during the operation of the barrier pulse. In the simulation, these particles are labelled as "LOST PARTICLE".

SIMULATION RESULTS OF NESR CASE

As described in the preceding sections, the simulation code with moving barrier pulses, electron cooling and IBS, gives results well in agreement with ESR experiment. Therefore we can proceed with confidence to investigate the NESR case with this code.

Parameters of the simulation for the NESR are given in Table 3. Barrier voltages are assumed as ±2kV which will be available with the present RF technology and are sufficient to compress the cooled beam. The time for moving the barrier pulse around half of the NESR circumference is selected as 0. 5 sec which is found to be slow enough to compress the cooled beam into the stacking area. Then the cycle time of barrier bucket operation is 2 sec.

Table 3: Parameters for simulation of the NESR case

Ion	$^{132}Sn^{50+}$, 740 MeV/u
Transverse emittance (1σ)	0.5π·mm·mrad
Ring revolution time	0.8922 μsec
Injected beam pulse width	0.4 μsec
Fractional momentum spread (1σ)	$2.5\cdot10^{-4}$
Ring slipping factor	-0.280
BB Voltage (*sin* wave)	±2kV
BB pulse width (1 λ)	200 nsec
Cycle time	2 sec
Cooler length	5 m
Electron current	1A
Beta function at cooler section (H/V)	22/10 m
Electron diameter	1 cm
Effective electron energy spread	10^{-4} eV

The electron current of the cooler, 1 Ampere is assumed as uniform in the cross sectional area of circle with diameter 1 cm. This diameter matches the ion beam at the cooler section with a beta function of 20m. The electron cooling is continuously applied to the ion beam during the whole process.

The evolution of momentum spread during electron cooling is given in Fig. 5 where we find that the time for cooling to equilibrium is around 0.15 sec. This cooling time is short enough to perform the whole accumulation cycle within 2 sec.

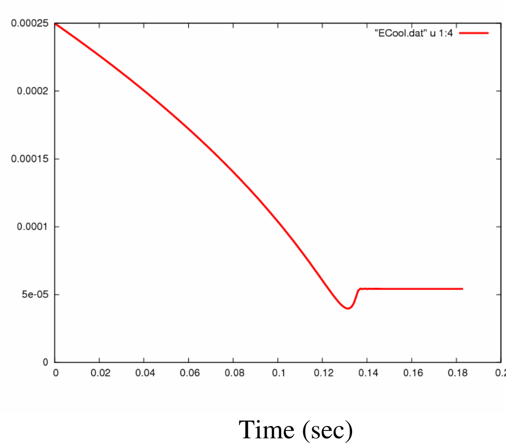

Figure 5: Evolution of momentum spread as a function of time in the NESR.

In Fig. 6 the calculated result of the stacked particle num-ber and the stacking efficiency are illustrated. After 10^{th} injection, the stacking efficiency is 92 % and the number of stacked ions reaches to $9.2\cdot10^{8}$.

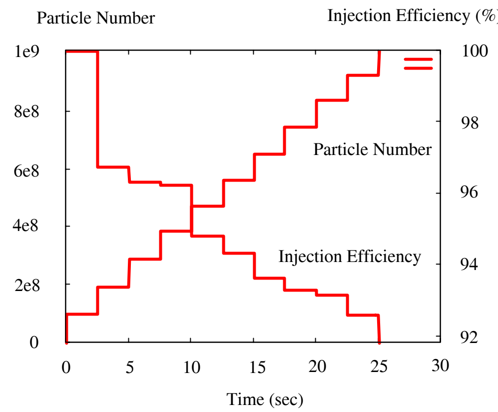

Figure 6: Calculated particle number and stacking efficiency at NESR.

CONCLUSION

We have studied numerically the process of ion beam stacking with moving barrier pulses assisted by electron cooling for the parameters of ESR and NESR. Results for the ESR are compared with the experimental data obtained for a 65 MeV/u Ar beam. The evolution of electron cooling and equilibrium values for momentum spread and transverse emittances are fairly well in agreement with the simulation results. Also the measured stacking efficiency is well reproduced by the simulation code. Therefore it can be reliably expected that a stacking efficiency of more than 90 % will be available with 2kV barrier voltages in the NESR. Another important subject related with the present accumulation method is the space charge repulsion force due the stacked high intensity beam, which reduces the effective barrier voltages and may result in the reduction of the stacked particle number in the accumulated area [6].

REFERENCES

[1] T. Katayama et al., Proc. of the International Workshop on Beam Cooling and Related Topics (COOL05), Illinois, 18-23, September 2005. AIPConf Proc. Vol. 821, p. 196.
[2] C. Dimopoulou et al., Phys. Rev. ST-AB **10**, (2007) 020101
[3] C. Dimopoulou et al., *in this Proceedings*.
[4] V. V. Parkhomchuk, NIM A441 (2000) 9.
[5] M. Martini, CERN PS/84-9 (AA) (1984)
[6] T. Kikuchi et al., *in this Proceedings.*