PARTICLE ACCUMULATION USING BARRIER BUCKET RF SYSTEM

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Abstract

Using of the RF burrier bucket system for the accumulation process was proposed for a few accelerator projects (FAIR, NICA). This rather new idea can bring new advantages to the accelerator physics. The principle possibility of this accumulation method with moving and stationary barrier bucket in the presence of the electron cooling was successfully demonstrated in the ESR storage ring last year. The article presents results of the numerical simulation and comparison with the experimental data. The aim of this work is an investigation of the accumulation process and optimization of the parameters of the cooling and barrier bucket systems. The numerical simulation of the accumulation process with barrier bucket systems for the ESR and NESR storage rings was done with BETACOOL code.

INTRODUCTION

One of the main goals of barrier buckets application at the New Experimental Storage Ring (NESR) of the FAIR project is to reach the high intensity of RIBs required by the internal experiments in the NESR and in particular by the electron-ion collider [1]. It is planned to stack the RIBs longitudinally at injection energy i.e. in the range 100-740 MeV/u. The stacking will be supported by electron cooling.

The Nuclotron-based Ion Collider fAcility (NICA) is a new accelerator complex being constructed at JINR aimed to provide collider experiments with heavy ions in the energy range from 1 to 4.5 GeV/u. To provide designed average luminosity of the order of 10^{27}cm^{-2}s^{-1} one needs to store in each ring of the collider of about $2\cdot10^{10}$ ions [2]. Injection chain of the collider permits to accelerate a single heavy ion bunch at intensity of the order of 10^9 particles. More attractive scheme of the beam storage in the collider ring relates to barrier buckets application and stacking under support by stochastic cooling system.

Presently two general schemes of the particle accumulation are discussed: with moving or with fixed barrier RF bucket.

In the scheme with moving barrier RF bucket (which is effectively used, for instance, in Fermilab's Recycler) the ion bunch is injected in the longitudinal gap prepared by two 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 or stochastic 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.

In the fixed barrier bucket scheme, one prepares a stationary (fixed in phase) voltage distribution consisting of two barrier pulses of opposite sign. The resulting stretched rf potential separates the longitudinal phase space into a stable and an unstable region. After injection onto the unstable region (potential maximum), the particles circulate along all phases and cooling application leads to their capture in the stable region of the phase space (potential well). After some time of the beam cooling the unstable region is free for a next injection without losing of the stored beam.

In an ideal case the maximum intensity of the stored beam is limited by intrabeam scattering (IBS) process. In equilibrium between IBS and cooling the stack momentum spread increases with increase of the stored particle number. When the momentum spread becomes to be larger than the barrier height the particles from the stack can penetrate into the injection region where they are killed by injection kicker pulse. The stacking efficiency depends on relation between injection repetition period and cooling time. In the real life the stacking efficiency can be seriously restricted by quality of the injection kicker pulse and imperfection of the barrier voltage pulse shape.

To investigate the stacking efficiency of the storage process both schemes (with moving and fixed barrier buckets) were experimentally tested at ESR with electron cooling of the ion beam [3]. The experimental results were used for benchmarking of computer codes developed for design of new storage rings. One of them, dedicated to simulation of the particle accumulation with barrier RF bucket at FAIR rings was developed in [4]. To compare predictions of different models new algorithms were implemented into BETACOOL program also [5]. In this article we discuss the results of the BETACOOL simulations.

PARTICLE ACCUMULATION WITH FIXED BARRIER BUCKET

Experiments with fixed burrier buckets were performed at beam and cooler parameters listed in the Table 1. Electron beam current was varied from 150 to 300 mA, injection repetition period t_{inj} was 3, 5 or 8 s. The revolution period of about 700 ns was separated by two sinusoidal burrier pulses into a stable region of duration of about 100 ns and unstable one, where the injection was taking place. For simplicity, the stacking process was simulated in BETACOOL with rectangular shape of the barrier pulses shown in Fig. 1 by red line.

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Table 1: Parameters of the ESR Experiments

Ion kind	$^{124}Xe^{54+}$
Particle number	10^7 / injection
Energy	154,4 MeV/u
Circumference	108.5 m
Initial momentum spread	5×10^{-4}
Initial hor./vert. emittance	0,7 mm mrad
RF voltage	120 V
Electron cooler length	1.8 m
Electron beam radius	2.5 cm
Effective electron temperature	10^{-3} eV
Cooler magnetic field	0.08 T
Beta functions in cooler hor./vert.	16 / 7 m

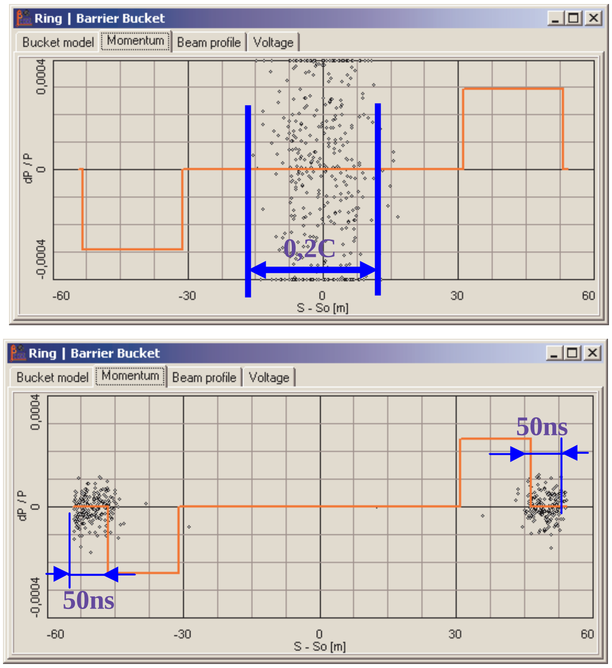

Figure 1: Particle positions in the longitudinal phase space. a) initial injection (0.2 C – means 20% of Circumference), b) after cooling.

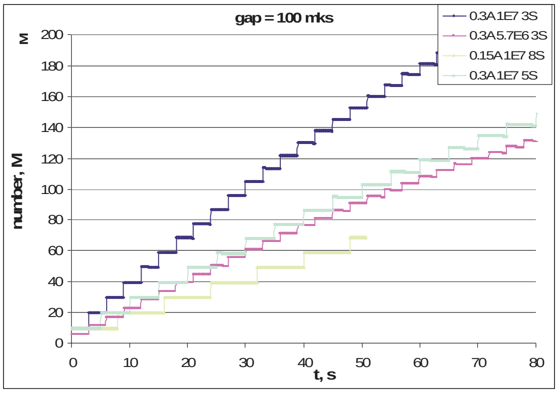

Figure 2: Stacking in 100 ns gap
a) $I_e = 0.3$ A, $N_i = 1{,}0\times10^7$, $t_{inj} = 3$ s;
b) $I_e = 0.3$ A, $N_i = 5{,}7\times10^6$, $t_{inj} = 3$ s;
c) $I_e = 0.15$ A, $N_i = 1{,}0\times10^7$, $t_{inj} = 8$ s;
d) $I_e = 0.3$ A, $N_i = 1{,}0\times10^7$, $t_{inj} = 5$ s;

The simulation show that the stacking rate is scaled with the intensity of the injection pulse at fixed injection repetition period (Fig. 2) and almost independent on the electron beam current. The last result follows to the fact that even the period of 3 s is sufficient for cooling of the injected beam. The ion life time was restricted by interaction with residual gas and approximately equal to 1000 s. At such conditions the stacking efficiency was closed to 100% up to the stack intensity of about 10^9 particles. So, the simulations demonstrate good capability of the stacking scheme for effective storage of intensive ion beams.

COMPARISON WITH EXPERIMETS

In the experiments at ESR the stack intensity saturated after a few tens of injections at the level of 10^8 particles (Fig.3). So large difference between simulations and experimental results can be explained by peculiarities of technical realization of the stacking scheme.

First of all, the kicker field does not equal zero after completion of the injection, but it oscillates with sufficient amplitude during a few ns. The kicker field distorts the stacked beam and leads to loss of the stored ions.

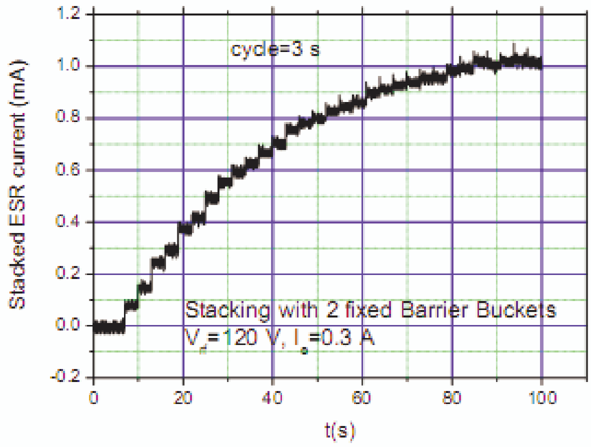

Figure 3: Example of the stacking process in experiment.

The stacking life time measured by switching off the injection and repeated kicker pulses was about 50 – 60 s. Simulation results of accumulation process with the lifetimes of 1000 and 50 sec are presented on Fig. 4. Red curve corresponds to experimental lifetime value and can be described by equation

$$N(t) = \frac{N_{inj}}{T_{inj}}\tau_{life}\left(1 - e^{-\frac{t}{\tau_{life}}}\right) \qquad (1)$$

In the case of τ_{life} = 50 sec the Formula (1) well reproduce the experimental dependence of the particle number on time during accumulation process. It means that in the experiments the particle losses are determined by the kicker pulse quality.

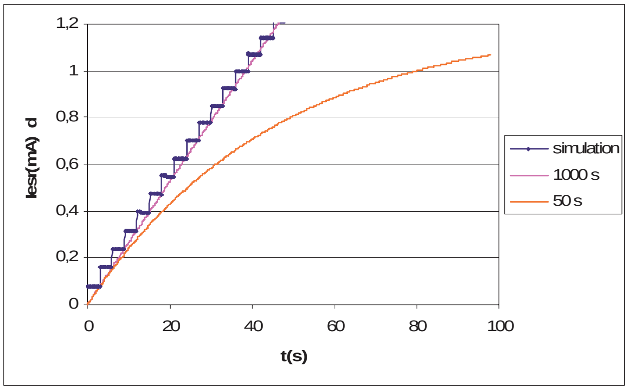

Figure 4: Simulation of the stacking process at different beam life time.

STACKING IN PRESENCE OF PARASITIC POTENTIAL WELL

Another possible limitation of the stacking efficiency relates to the shape of the burrier voltage pulse. In the experiment the imperfection of the barrier pulse formed a parasitic potential well in the injection region. The particles trapped in this well are lost at new injection. To investigate this effect the stacking process was simulated at the RF shape shown in the Fig. 5, the corresponding RF potential is shown in the Fig. 6.

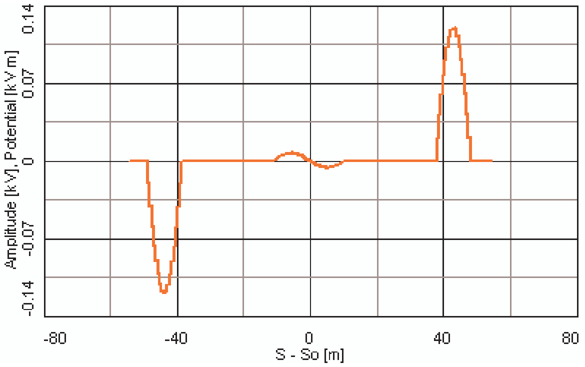

Figure 5: Barrier pulse shape with parasitic potential well with amplitude 7 V.

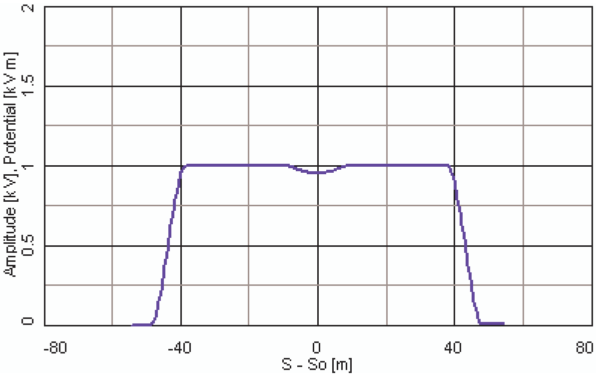

Figure 6: The potential distributions with additional potential well in the injection region.

The losses during new injection of the particles trapped in this additional well lead to 60% decrease of the stack intensity after completion of the accumulation process (Fig. 7). However, the situation can be improved by small shift of the electron energy. In this case the electron cooling removes the particles from the additional well and the stacking efficiency is not less than for an ideal barrier pulse shape.

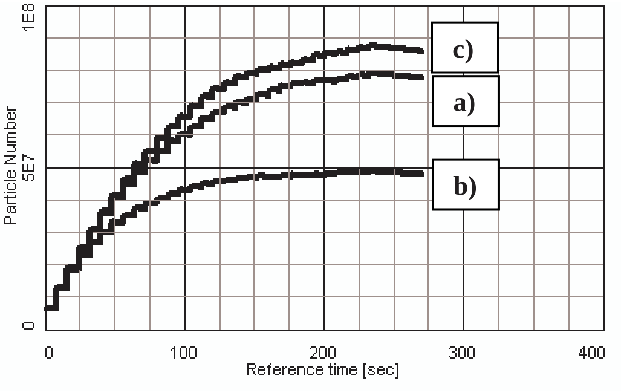

Figure 7: The stacking process without additional potential well (a), with the additional well (b) and tuned electron energy (c), with the potential well and electron momentum shifted by $\Delta p/p = 5\times10^{-5}$. Injection pulse intensity is $6{,}5\times10^{6}$ ions, interval between injections is 8 s.

SIMULATIONS FOR NESR

Stacking of RIBs in the NESR using fixed barrier buckets was simulated for Sn isotope (Table 2). The longitudinal phase space was divided by equal parts with help of two barrier pulses of half-sinusoidal shape.

Table 2: NESR Parameters

Ion kind	$^{132}\mathrm{Sn}^{50+}$
Particle number/ injection	$1{,}0\times10^{8}$
Energy	740 MeV/u
Circumference	222.8 m
Initial momentum spread	$6{,}5\times10^{-4}$
Initial hor./vert. emittance	0,125 mm mrad
RF voltage	2000 V
Interval between injection	2 sec
Electron cooler length	5 m
Electron beam current	1 A
Electron beam radius	0.5 cm
Effective electron temperature (Parkhomchuk's formula)	10^{-3} eV
Cooler magnetic field	0.2 T
Beta functions in cooler hor./vert.	10 / 22 m

The stacking process develops at constant time constant up to about $3.6\cdot10^{9}$ ions. At this intensity the beam momentum spread reaches the barrier height and IBS pushes the ions to unstable region, where injections are performed. After that the intensity of the stacked beam tends to saturation (Fig. 8).

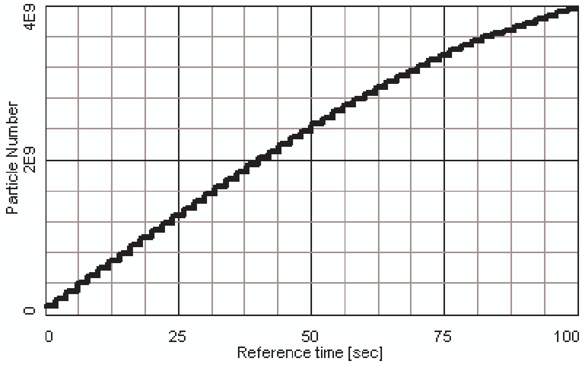

Figure 8: Storage process in NESR with fixed barrier buckets.

At the same conditions the stacking process with moving barrier buckets of rectangular shape was simulated. The stacking efficiency in this case is slightly less than with fixed one. It does not relate to IBS process and can be explained by technical realization of the stacking process. When the coasting stack circulates in the ring and the barrier voltages are switched on in order to prepare free space for a new injection, some part of the beam is trapped in a stable region between the pulses (Fig. 9). When the pulses are moved away from each other to prepare the empty space these particles oscillate between the pulses and part of them is lost at the new injection. For the pulse shape shown in the Fig.9 the stack intensity saturates at the level of about $8\cdot10^8$ particles.

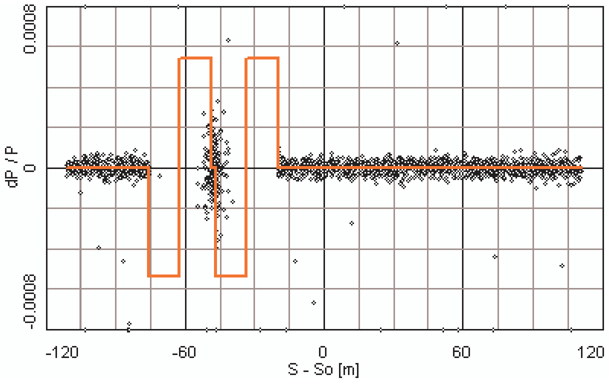

Figure 9: Particle distribution in the longitudinal phase plane after switching on the barrier voltage.

The stacking efficiency can be improved by accurate optimization of the barrier pulse shape and the simulations show that it can reach almost the same level as at fixed buckets.

CONCLUSIONS

Simulations and experiments showed high efficiency of a beam stacking using the barrier bucket technique. Further investigation of the stacking procedure using the RF barrier bucket method is related to the improvement of the BETACOOL code, new experiments at ESR, numerical simulation of the experimental results and optimization of the accumulation process for NESR. Simulations of the ion stacking in the NICA collider are in progress now.

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