# EXPERIMENTAL DEMONSTRATION OF LONGITUDINAL ION BEAM ACCUMULATION WITH ELECTRON COOLING *

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*Abstract*

Recently, two longitudinal beam compression methods have been successfully tested in the Experimental Storage Ring (ESR) at GSI. The first employs barrier bucket pulses, either moving or fixed in time, the second makes use of multiple injections around the unstable fixed point of a sinusoidal rf bucket at harmonic number $h$=1. In all cases, the stacking is supported by continuous electron cooling. Using the beam diagnostic devices in the ring both stacking processes were observed. The dependence of the accumulation performance on the available rf potential, the electron cooling strength as well as on the synchronization conditions between injection kicker pulse and rf wave was investigated. These experimental results provide the proof of principle for the planned fast stacking of rare isotope beams aiming at high luminosities in the New Experimental Storage Ring (NESR) of the FAIR project.

## INTRODUCTION

In order to reach the high intensity of rare isotope beams (RIBs) required by the experiments in the NESR [1, 2] it is planned to stack the RIBs longitudinally at injection energy. In this frame, different longitudinal beam accumulation schemes in combination with electron cooling have been investigated by simulations and experiments.

The first method uses short barrier bucket (BB) pulses provided by a broadband rf system [3]. In the moving BB scheme, two sinusoidal BB pulses are introduced into the beam. One stays stationary while the other is shifted in phase to compress the beam. Thus, a gap is created where new beam can be injected. In the fixed BB scheme, one prepares a stationary (fixed in phase) distribution consisting of (or similar to) two half-sine 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 drift to the stable region of the potential. After some time the unstable region is free for a next injection without losing stored beam.

The second method uses a $h$=1 rf system for bunching of the circulating beam and injection of a new bunch onto the unstable fixed point in longitudinal phase space. The rf voltage is raised adiabatically so as to confine the bunch in a small fraction of the ring circumference. A new bunch is injected onto the free part of the circumference. Then the voltage is decreased (rather non-adiabatically in order to avoid dilution of the new bunch) to let the beam debunch.

In all schemes, continuous electron cooling counteracts heating of the stack during the rf compression and merges the stack with the freshly injected bunch. The required rf voltages for the compression are moderate since the momentum spread of the cooled stack is small ($< 10^{-4}$). The stack is subjected repeatedly to the same procedure until an equilibrium between beam losses and injection rate is reached.

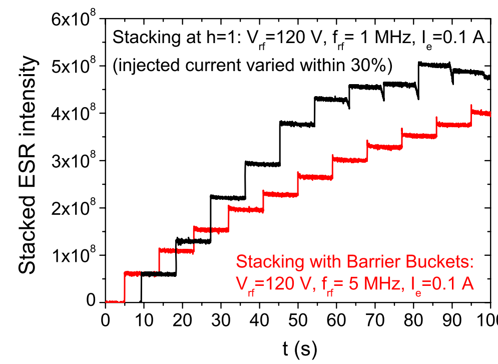


Figure 1: Demonstration of beam stacking with moving BB and with $h$=1 rf with a $^{40}Ar^{18+}$ beam at 65.3 MeV/u. The stacking cycle was 9 s, the electron cooling current 0.1 A.

## EXPERIMENTAL PROCEDURE

The stacking options mentioned above were tested in the ESR [4] with ion beams injected from the synchrotron SIS. In the first run, stacking with moving BB and with the $h$=1 rf system was demonstrated with a $^{40}Ar^{18+}$ beam at 65.3 MeV/u ($T_{rev} = 1.017$ $\mu$s)[5]. In the second run, for the first time stacking with fixed BB and again stacking with the $h$=1 rf system were tested with a $^{124}Xe^{54+}$ beam at 154.4 MeV/u ($T_{rev} = 704$ ns). The SIS and ESR rf systems were synchronised to operate at $h$=2 and $h$=1, respectively, since the SIS has double the circumference of the ESR. One of the two SIS bunches is fast extracted to the ESR. The ESR injection kicker pulse was typically 500 ns long (100 ns rise/fall time, 300 ns flat top).

The height (in momentum) of the rf barrier for a sinusoidal pulse is $\delta_B = (2QeV_{rf}/\pi\beta^2\eta h E_{0,tot})^{1/2}$ where $E_{0,tot} = \gamma A m_u c^2$ is the total energy ($m_u c^2$=931.5 MeV is the nucleon mass) and $Q$ the charge state of the ion. For the BB pulses a "harmonic" number $h = T_{rev}/T_B$ is defined. Hence, at the same $V_{rf}$ the confining potential of the BB system is $\sqrt{h}$ lower than for the $h$=1 rf.

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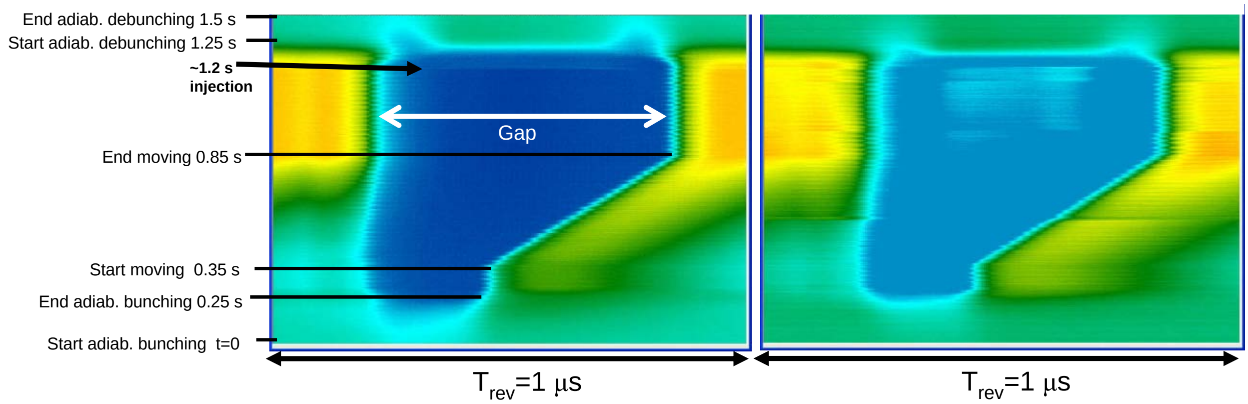


Figure 2: Stacking with moving sinusoidal BB pulses of $T_B$=200 ns period. Signal (arbitrary units) registered in the BPM (one frame every 200 $T_{rev}$). Dark blue to orange: zero to high beam signal. BB voltage= 120 V (left); 20 V (right).

At the equilibrium between electron cooling and intra-beam scattering, the measured momentum spread $\delta p/p$ of the stored beam scaled with the particle number $N_i$ - generally with the linear particle density $N_i/B$, where $B = T_{stack}/T_{rev}$ is the bunching factor- and cooling current $I_e$ as $(\delta p/p) \sim (N_i/B)^{0.36} I_e^{-0.3}$.

The increase of beam intensity during the stacking in the ESR was monitored with the dc current transformer as shown for example in Fig. 1.

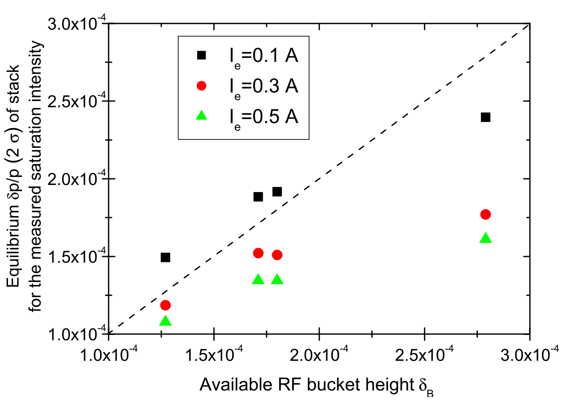


Figure 3: Stacking with moving BB pulses. Momentum spread of the accumulated $^{40}Ar^{18+}$ beam compared with the rf bucket height for different electron cooling currents.

## STACKING WITH MOVING BB

Fig. 2 shows the $^{40}Ar^{18+}$ beam signal measured in the beam position monitor (BPM) and illustrates the procedure. Two BB pulses are adiabatically introduced into the cooled coasting beam. One stays stationary while the other is shifted in phase to compress the beam. At t $\approx$ 1.2 s a new bunch is injected into the gap between the barriers and subsequently debunches because the voltage is not sufficient to capture the particles. Then, the BB pulses are switched off adiabatically, while the beam is being continuously cooled. For 120 V BB voltage, the stack and the injected bunch are well separated at the instant of the new injection, whereas the lower voltage of 20 V is not sufficient to confine the stack ions with high momentum spread.

The momentum spread of the stack was estimated by applying the above scaling law, where $N_i$ is the measured saturation intenstity and the stack length $T_{stack}$=400 ns includes 75% of the uniform distribution as measured in the BPM. The results are plotted in Fig. 3. For large bucket height and strong cooling the stacked intensity was limited due to the onset of coherent transverse instabilities.

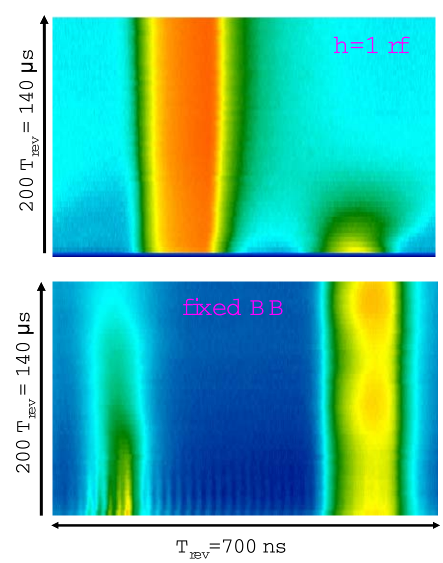


Figure 4: Stacking with continuously applied $h$=1 rf and with fixed BB pulses. Signal (arbitrary units) registered in the BPM during the first 200 revolutions of the $^{124}Xe^{54+}$ beam at 154.4 MeV/u after injection. Dark blue to orange: zero to high beam signal. In both cases the fast debunching of the beam injected onto the unstable region of the rf potential is observed.

## STACKING WITH THE $H$=1 RF

Stacking at $h$=1 was investigated in a similar way. At saturation intensity, the stacked bunch length was measured in the BPM and the corresponding $\delta p/p$

was calculated from the rf bucket formula $\sigma_t/T_{rev} = (\beta^2\eta E_{0,tot}/2\pi QehV_{rf})^{1/2}(\delta p/p)$ and compared with $\delta_B$. The conclusion is that the stacked bunch occupied about 20% of the ring circumference and filled 50-60% of the bucket height, for applied voltages in the range 30-120 V. Within the BPM resolution (10 ns), the bunch length was found to be independent of $I_e$. The measured relative phase of the stacked bunch with respect to the injected bunch indicated that the kicker pulse overlapped with the tail of the stack, causing particle losses at every injection. The situation was improved in the experiment with the $^{124}Xe^{54+}$ beam using higher rf voltages up to 500 V and a shorter kicker pulse better synchronized with the rf system. Thus, a clear separation between the stacked and injected bunch was achieved as shown in Fig. 4.

## STACKING WITH FIXED BB

Since the generation of short (100 ns) pure half-sine pulses was technically demanding for the existing rf system, two sinusoidal BB pulses of $T_B$=200 ns period shifted relative to each other by 180° were used to create the stretched rf potential. Fig. 5 shows the total rf voltage pulse applied to the cavity and its time-intergral i.e. the rf potential. The voltage signal measured at the cavity gap and its potential are also shown for comparison. The approximate location of the stack and injected bunch with respect to the applied voltage pulse (yellow line) are indicated, too. Because of the effectively long injection kicker pulse, the longer region had to be used for injection, leaving a restricted part of the circumference ($\sim$ 20 %) for the stack, as can be deduced from the BPM signal in Fig. 4. Notice in Fig. 4 that, as expected, the injected beam debunches slower in the stretched potential of the fixed BB than in the harmonic potential of the $h$=1 rf system.

The accumulation curve from the dc current transformer in Fig. 6 confirms the successful stacking by fixed BB.

## OUTLOOK

Further analysis is under way in order to compare the performance and scope of application of the different stacking methods. The $h$=1 rf but also the fixed BB are clearly advantageous because of their simplicity. These first results indicate that stacking with fixed BB is very promising because (i) the whole procedure is quite fast even though it relies on the synchrotron motion of a phase-space cooled beam and (ii) the stack remains practically undisturbed.

The experimental data are used to benchmark dedicated beam dynamics simulation codes [6], which, in turn, provide predictions for the stacking performance in the NESR. For instance, under realistic operation of the electron cooling and the rf systems, a maximum moving BB voltage of 2 kV is sufficient to compress cooled beams in the NESR. Provided that the quality of the injected pre-cooled beam allows cooling times below 1 s in the NESR [5], the stacking cycle is about 2 s, i.e. optimal in order to cope with the

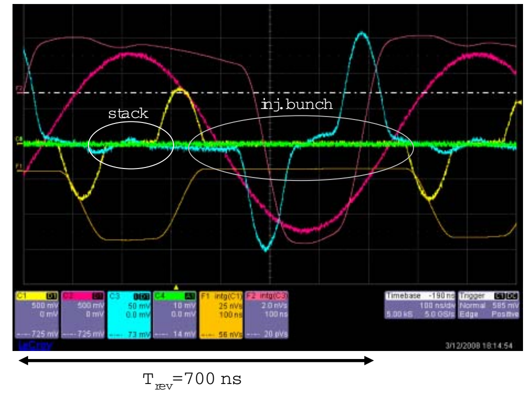


Figure 5: Realisation of fixed BB. Applied BB voltage pulse (yellow line) and its potential (orange line). Measured rf voltage (blue line) and its potential (thin magenta line). Carrier rf wave at $h$=1 used to synchronise the SIS and ESR rf systems (thick magenta line).

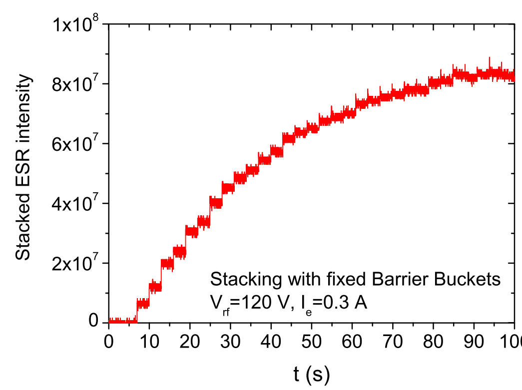


Figure 6: Experimental demonstration of very fast stacking with fixed BB with a $^{124}Xe^{54+}$ beam at 154.4 MeV/u in the ESR. The stacking cycle was <3 s, the BB peak voltage 120 V, the electron cooling current 0.3 A.

short RIB lifetimes and to profit from the cycle of 1.5 s of the synchrotron SIS100, where the primary heavy ion beam is accelerated.

The experimental results at the ESR demonstrate the principle and feasibility of the stacking methods and confirm the requirements for the NESR systems, namely, faster electron cooling, a BB system with 2 kV peak voltage with the option to operate as $h$=1 rf system, an adjustable injection kicker pulse and appropriate beam diagnostics.

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