LONGITUDINAL ACCUMULATION OF ION BEAMS IN THE ESR SUPPORTED BY ELECTRON COOLING*

C. Dimopoulou, B. Franzke, T. Katayama, G. Schreiber, M. Steck, GSI, Darmstadt, Germany
D. Möhl, CERN, Geneva, Switzerland

Abstract

Recently, two longitudinal beam compression schemes have been successfully tested in the Experimental Storage Ring (ESR) at GSI with a beam of bare Ar ions at 65 MeV/u injected from the synchrotron SIS. The first employs Barrier Bucket pulses, the second makes use of multiple injections around the unstable fixed point of a sinusoidal rf bucket at h=1. In both cases, continuous application of electron cooling maintains the stack and merges it with the freshly injected beam. These experiments provide the proof of principle for the planned fast stacking of Rare Isotope Beams (RIBs) in the New Experimental Storage Ring (NESR) of the FAIR project.

INTRODUCTION

In order to reach the high intensity of RIBs required by the internal experiments in the NESR [1, 2] and in particular by the electron-ion collider [3], it is planned to stack the RIBs longitudinally at injection energy i.e. in the range 100-740 MeV/u [4]. The stacking will be supported by electron cooling. A stacking cycle time, i.e. the time between 2 successive injections, below 2 s would be optimal because of the short RIB lifetimes and in order to profit from the planned cycle time of 1.5 s of SIS100, where the primary heavy ion beam is accelerated. In this frame, two options of longitudinal beam accumulation have been investigated by beam dynamics simulations and by experiments in the existing ESR at GSI.

The first option uses a broadband Barrier Bucket (BB) rf system. Dedicated beam dynamics simulations [5] show that a maximum voltage of 2 kV is sufficient to compress cooled beams in the NESR. The stacking cycle time could be about 2 s, provided that the quality of the injected pre-cooled beam from the CR/RESR complex [2] allows cooling times below 1 s in the NESR. This is demonstrated in Fig. 1. At t=0 a bunch is injected between the BB sine pulses of 100 ns period. The injected beam debunches because the voltage is not sufficient to capture the particles. The BB pulses are decreased and switched off at t=0.2 s, while the beam is being continuously cooled. For the injected beam, an initial emittance of 0.5 π mm mrad and energy spread of 1.5 MeV/u was assumed. They correspond to the 2σ design values for the pre-cooled beam in CR with an additional 30% increase of the longitudinal emittance due to diffusion processes during the transfer through the RESR to the NESR. Parkhomchuk's formula [6] is used for the cooling rate, for an electron beam density of 3.2×10^{8} cm^{-3}, a magnetic field strength of 0.2 T in the cooling section and an effective electron velocity corresponding to magnetic field errors of 5×10^{-5}. The resulting cooling time is about 0.8 s. Then, the BB pulses are adiabatically introduced into the beam and increased to 2 kV. One stays stationary while the other is shifted in phase to compress the cooled beam. At t=2 s a new bunch is injected.

The second option 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 [7]. 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 both schemes, continuous application of electron cooling (i) counteracts heating of the stack during the rf compression and (ii) merges the stack with the freshly injected bunch. The required rf voltages for the longitudinal beam compression are moderate since the momentum spread of the cooled stack is small (of the order of 10^{-4} or better). The cooled stack is repeatedly subjected to the same procedure until an equilibrium between beam losses and injection rate is reached.

EXPERIMENTAL PROCEDURE

Both stacking options have been tested in the ESR [8] under the same conditions. The experiments were performed with a $^{40}Ar^{18+}$ beam at 65.3 MeV/u injected from the synchrotron SIS. The SIS and ESR rf systems were synchronised to operate at f_{rf}=983 kHz, at h=2 and h=1, respectively, since the SIS has the double circumference of the ESR. One of the two bunches in SIS is fast extracted to the ESR. The bunches in SIS, measured with a sum pickup, had a FWHM between 300-350 ns. The ESR injection kicker pulse was typically 500 ns long (100 ns rise/fall time, 300 ns flat top). It was not straightforward to further reduce the kicker pulse length during the experiment, which restricted the flexibility in the longitudinal manipulation during the stacking with BB. In the case of stacking with the sinusoidal rf at h=1, a longer kicker pulse could in principle have been advantageous to reach higher injection efficiency. However, as it will be explained below, the experimental results indicate that the synchronisation of the kicker with the rf pulse at h=1 was not perfect and, as a consequence, losses occurred during stacking.

* Work supported by EU FAIR Design Study COOLSB11

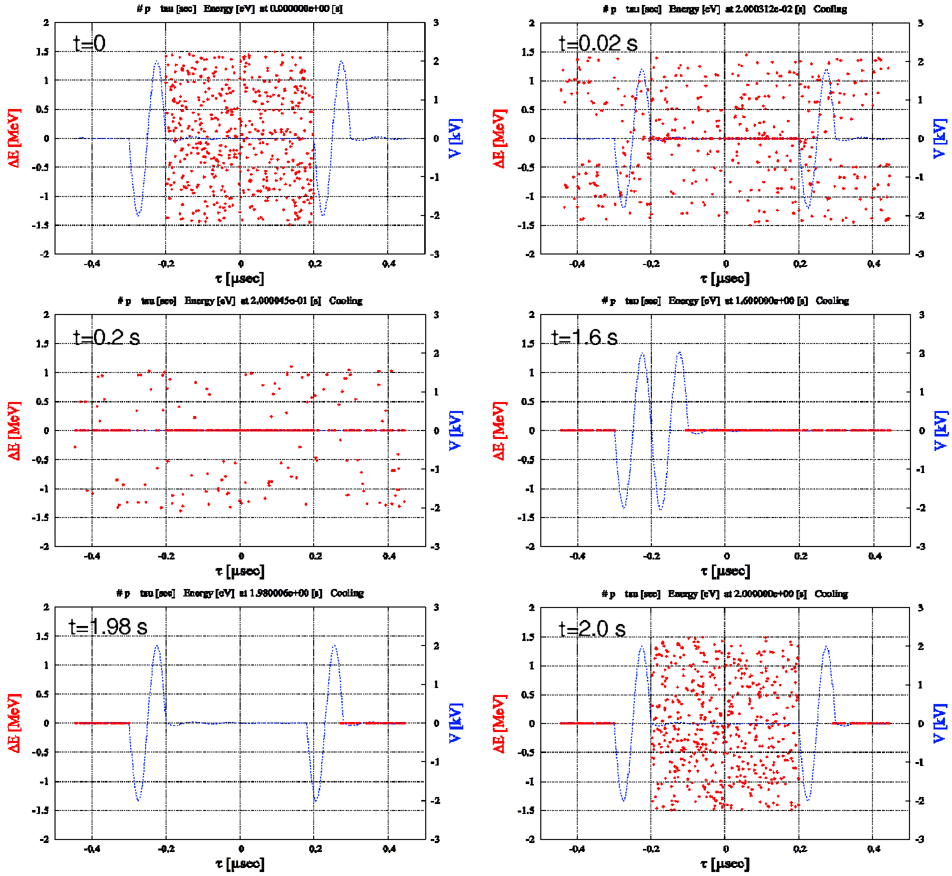

Figure 1: Accumulation of the 740 MeV/u ^{132}Sn^{50+} beam (0.9 μs revolution period) in the NESR by Barrier Buckets and electron cooling. Solid lines: barrier voltage; Dots: particle distribution in the longitudinal phase space. Top left to bottom right: beam injection, debunching, cooling, application of the BB pulses, compression of the stack by moving one barrier, new injection into the gap between the barriers.

Measurements of the horizontal beam profile with the rest gas monitor and of the momentum spread with the longitudinal Schottky pickup showed that the injected beam was cooled down to the equilibrium within about 13 s, for operation of the ESR electron cooler [9] with an electron beam density of 3×10^6cm^{-3} (0.1 A, 2.5 cm beam radius) and a magnetic field strength of 0.07 T in the cooling section.

At the equilibrium between the applied electron cooling and Intra Beam Scattering (IBS), the horizontal emittance and momentum spread of the stored coasting beam were measured with the rest gas beam profile monitor and the longitudinal Schottky pickup, respectively. They were found to scale with the particle number N_i for coasting beam- more generally with the beam linear density N_i/B, where $B = T_{bunch(stack)}/T_{rev}$ is the bunching factor- and cooling current I_e as

$$(\Delta p/p)_{equil} \sim (N_i/B)^{0.36} I_e^{-0.3} \quad (1)$$

$$(\epsilon_{h,v})_{equil} \sim (N_i/B)^{0.41} I_e^{-0.3} \quad (2)$$

in accordance with the results of previous systematic experimental studies in the ESR [10]. For 10^8 ions and I_e=0.1 A, $(\Delta p/p)_{equil}$=10^{-4}, $(\epsilon_h)_{equil}$=1 π mm mrad (2σ values).

The revolution period in the ESR was T_{rev}=1.017 μs, i.e. sufficiently long to allow stacking with the sine-shaped BB pulses of T_B=200 ns period provided from the BB cavity. The maximum height (in momentum spread) of the rf barrier δ_B is given by the usual formula for a sinusoidal rf pulse

$$\delta_B = \sqrt{\frac{2QeV_{rf}}{\pi\beta^2\eta h E_{0,tot}}} \quad (3)$$

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. The height δ_B is defined so that the maximum height of the separatrix is at $\Delta p/p = \pm\delta_B$. For the BB pulses of period T_B a "harmonic" number $h = T_{rev}/T_B \approx 5$ is defined. Hence, at the same voltage the confining potential of the BB system is $\sqrt{5}$ lower than for the h=1 rf.

For both methods, the increase of beam intensity in the ESR during the stacking was measured with the dc beam current transformer. An example is shown in Fig. 3. The corresponding accumulation efficiency curves i.e. the increment of the ESR beam current per injected shot are also shown. A beam current of 0.3 mA corresponds to 10^8 ^{40}Ar^{18+} ions at 65.3 MeV/u in the ESR.

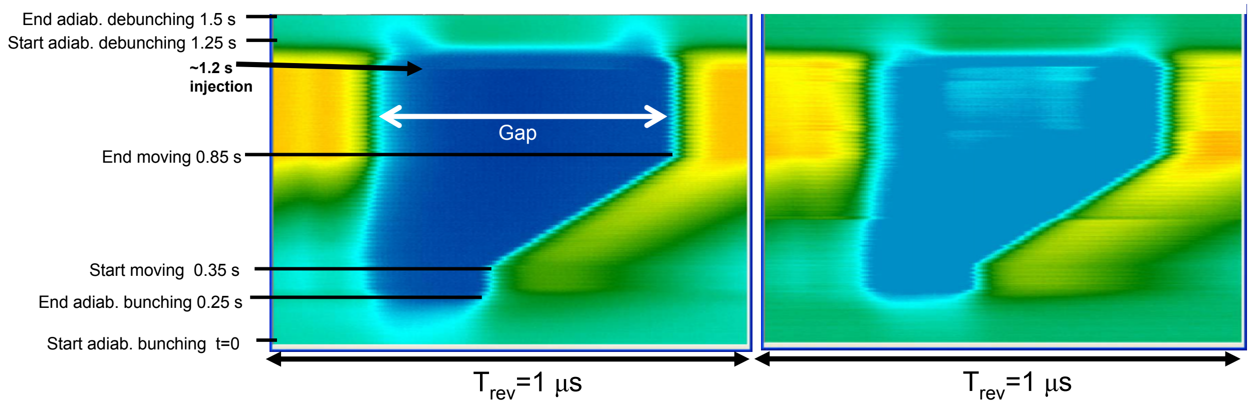

Figure 2: Longitudinal beam accumulation with Barrier Bucket pulses and electron cooling. Signal (arbitrary units) registered in the ESR beam position monitor. Colour code (dark blue to orange): zero to high beam signal. One frame was recorded every 200 revolutions for a total time of 1.5 s. The stacking cycle was 9 s and the electron beam current in the cooler 0.1 A. The period of the barrier pulses was 200 ns. Left: BB voltage=120 V; Right: BB Voltage=20 V.

STACKING WITH BARRIER BUCKETS

Fig. 2 shows the $^{40}Ar^{18+}$ beam signal measured in the ESR pickup during the stacking with BB and illustrates the experimental procedure, which was similar to the one in Fig. 1. For 120 V BB voltage, the stack and the injected bunch are well separated at the instant of the new injection (t$\sim$1.2 s), whereas the lower voltage of 20 V is not sufficient to confine the stack particles with high momentum spread. The barrier pulse moves in phase by 400 ns (141.6°) within 0.5 s i.e. with a rate of 8×10^{-7} much slower than the synchrotron motion rate $\Delta f/f = \eta\Delta p/p \approx 7\times10^{-5}$ of the cooled stack with $\Delta p/p \approx 10^{-4}$. The saturated value I_{ESR} of the stacked beam intensity in the ESR was measured with the current transformer for different parameters of the rf system (voltage, T_B) and electron currents. As expected, I_{ESR} increases with increasing available rf bucket height δ_B and cooling strength. In a further analysis, the momentum spread of the stacked beam at equilibrium between cooling and IBS can be estimated by applying the measured scaling law of Eq. 1, where N_i is now the measured saturated stack intenstity and taking into account the bunching factor $B = T_{stack}/T_{rev}$. The distribution of the stack measured in the pickup (see also Fig. 2) was uniform with a length (including 75% of the distribution) T_{stack}=400 ns, 300 ns for pulses of T_B=200 ns, 300 ns, respectively. The resulting $\Delta p/p$ of the saturated stack is plotted in Fig. 4 versus δ_B , for different I_e. For the largest δ_B and strong cooling the accumulated beam intensity was limited due to the onset of observed coherent transverse instabilities. Comparison of the experimental results with beam dynamics simulations is given in [5].

STACKING WITH THE HARMONIC *H*=1

Stacking by multiple injections on the unstable fixed point of the sinosoidal rf at h=1 was investigated experimentally in a similar way: The cooled coasting beam is bunched adiabatically within 0.25 s. Then, the new beam is injected. The rf voltage is switched off within 1 ms after injection to allow fast debunching and merging of the bunch with the stack for cooling. The energy of the electron cooler was finely adjusted to the energy of the synchronous particle in the rf bucket by minimising the bunch length measured with the pickup.

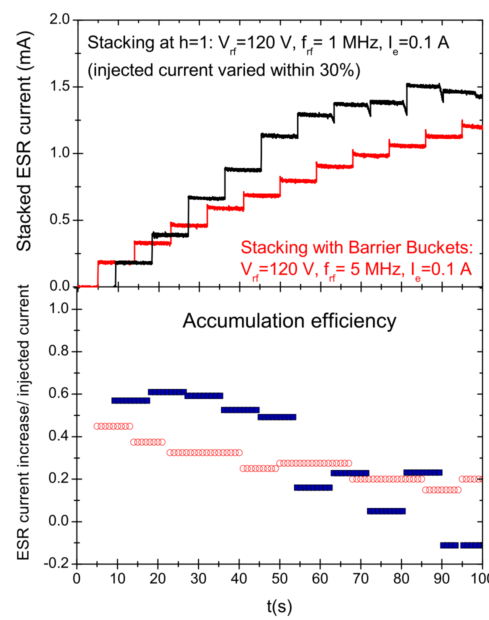

Figure 3: Experimental demonstration of the two proposed longitudinal accumulation methods with an $^{40}Ar^{18+}$ beam at 65.3 MeV/u in the ESR. The stacking cycle was 9 s, the electron cooling current 0.1 A. Because of the different rf frequency, for the same voltage, stacking at h=1 offers $\sqrt{5}$ stronger confinement than with BB. Variations of the injected current are due to source current variations.

Surprisingly, as shown in Fig. 5, the dependence of the accumulated intensity on I_e is very slight, in contrast to the results for the BB stacking. At saturation intensity, the

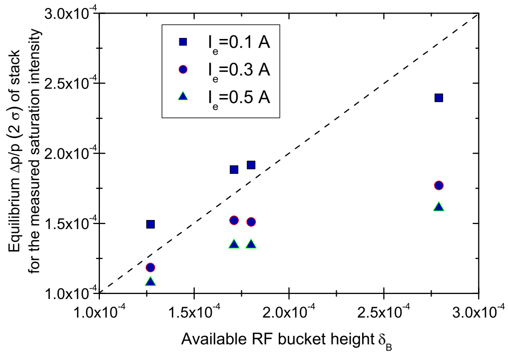

Figure 4: Longitudinal beam accumulation with Barrier Bucket pulses and electron cooling. Momentum spread of the accumulated $^{40}Ar^{18+}$ beam in comparison with the rf bucket height for different electron cooling currents.

stacked bunch length was measured in the pickup and the corresponding $\Delta p/p$ was calculated from the rf bucket formula:

$$\frac{\sigma_t}{T_{rev}} = \sqrt{\frac{\beta^2 \eta E_{0,tot}}{2\pi QehV_{rf}}}\frac{\Delta p}{p} \tag{4}$$

It is compared in Fig. 5 with δ_B for the corresponding rf voltage. Within the pickup resolution (10 ns), the bunch length was found to be independent on I_e. The conclusion is that at saturation intensity the stacked bunch occupied about 20% of the ring circumference and filled essentially 50-60% of the momentum acceptance of the rf bucket at h=1, for all applied voltages in the range 30-120 V.

The results in Fig. 3 suggest that the injection efficiency was not optimal. In particular, from the relative phase of the stacked bunch with respect to the freshly injected bunch as measured in the pickup, it follows that the kicker pulse overlapped in time with the tail of the stack, so that stack particles were lost at every new injection. In other words, the new bunch was not injected exactly on the unstable fixed point of the separatrix but rather close to the stack. Another remark concerns the bunching time of 0.25 s: It was indeed adiabatic with respect to the synchrotron motion but might have been rather fast with respect to the cooling time of the stack. A dedicated experiment is planned in the ESR in order to improve the stacking procedure at h=1.

We have checked that, for both stacking methods, the maximum accumulated intensity of $4-5\times10^8$ ions was not limited by space charge effects. Typically, for bunching factors of 0.2-0.4 and strong cooling (I_e=0.5 A), the stack transverse emittance calculated from the scaling law in Eq. 2 was 2 mm mrad. For a maximum incoherent Laslett tune shift of 0.1, the space charge limit was $2-3\times10^9$ ions i.e. well above the considered maximum stacked intensity. The longitudinal space charge limit from the Keil-Schnell-Boussard criterion [12] was even higher i.e. $\approx 4\times10^{10}$ ions for a cooled stack with $\Delta p/p \approx 10^{-4}$.

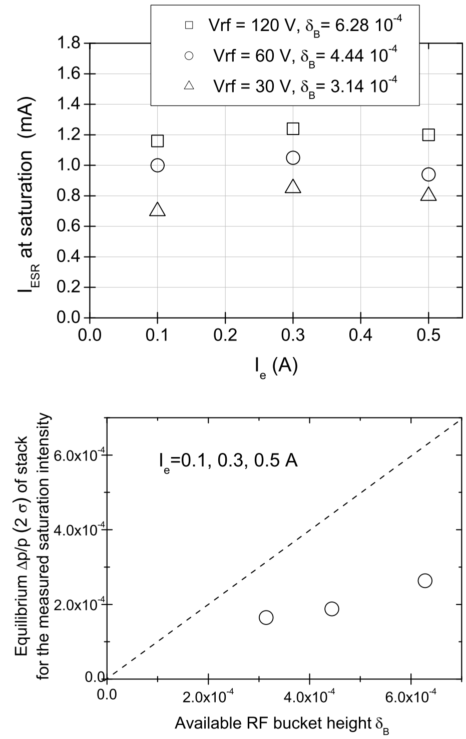

Figure 5: Longitudinal beam accumulation with h=1 rf and electron cooling. Upper part: Stacked beam intensity measured with the current transformer for different rf voltages and electron currents. Lower part: Momentum spread of the stacked $^{40}Ar^{18+}$ beam (proportional to its measured bunch length) compared to the rf bucket height.

OUTLOOK

These results confirm the requirements for the NESR systems, namely, faster electron cooling [11], a BB system with 2 kV peak voltage, adjustable injection kicker pulse and appropriate beam diagnostics.

REFERENCES

[1] C. Dimopoulou et al., Phys. Rev. ST Accel. Beams 10 (2007) 020101.

[2] FAIR Baseline Technical Design Report, GSI (2006). http://www.gsi.de/fair/reports/.

[3] I.A. Koop et al., Proc. of EPAC, Paris (2002) 620.

[4] B. Franzke et al., NIM A 532 (2004) 97.

[5] T. Katayama, these proceedings.

[6] V.V. Parkhomchuk, NIM A 441 (2000) 9.

[7] S. Baird et al., IEEE Proc. of PAC (1989) 645.

[8] B. Franzke, NIM B 24/25 (1987) 18.

[9] M. Steck et al., NIM A 532 (2004) 357.

[10] M. Steck et al, CERN Yellow Report 94-03 (1993) 395.

[11] V.V. Parkhomchuk et al., GSI-Acc-Report-2005-04-001.

[12] J. Bosser et al., NIM A 441 (2000) 1.