DEMONSTRATION OF LONGITUDINAL STACKING IN THE ESR WITH BARRIER BUCKETS AND STOCHASTIC COOLING

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Abstract

Fast longitudinal beam accumulation has been demonstrated in the ESR at GSI with an ^{40}Ar^{18+} beam coming from the synchrotron SIS18 at 400 MeV/u. Continuous application of stochastic cooling in all three phase space directions merged the stack with the newly injected bunch. Longitudinal beam compression was achieved either by using short barrier bucket rf pulses or by successive injections onto the unstable fixed point of the rf bucket at h=1. This recent experiment in the ESR provides the proof of principle for the longitudinal stacking of antiprotons in the FAIR project. It is planned to accumulate pre-cooled antiprotons in the HESR, injected from the CR.

INTRODUCTION

One of the four pillars of the physics program at FAIR [1] is based on a high production rate of antiprotons for hadron physics with high energy antiprotons, but also on the availability of low energy antiprotons. For optimum production rate it was proposed to have a system of collector and accumulator ring after the antiproton production target in order to have fast collection, stochastic precooling and accumulation of the hot antiprotons emerging from the target. After the accumulator ring the cooled antiprotons then could be sent either to a high energy storage ring (HESR) for experiments with stored antiprotons or to another storage ring (NESR) which constitutes the first stage of deceleration to lowest energy. Due to funding limitations, it was decided to start the FAIR project with high energy antiprotons at reduced intensity.

The first stage antiproton production concept of FAIR now comprises the following ingredients. A high intensity 70 MeV proton beam from a new linac will be injected into the existing synchrotron SIS18 which boosts it to 4 GeV. The new 100 Tm synchrotron SIS100 will accelerate the protons to 29 GeV. The ramping cycle can be as short as 2.5 s, but as the antiproton production rate is limited by the stochastic pre-cooling a repetition cycle of 10 s is foreseen, with an option to upgrade to a 5 s cycle. A single short ($\approx$50 ns) bunch of up to 2×10^{13} protons will be extracted towards a nickel target for antiproton production followed by a magnetic horn to focus the divergent antiproton bunch. A magnetic separator selects 3 GeV antiprotons which are subsequently transported to the large acceptance collector ring CR [2]. Bunch rotation and debunching transforms the short bunch into a nearly coasting beam with a reduced momentum spread. Stochastic cooling is applied to reduce the longitudinal momentum spread and both transverse emittances. In contrast to the old scheme with a dedicated accumulator ring, the cooled antiprotons will be transferred directly to the high energy storage ring HESR [3], which in the new scheme also serves as accumulator ring.

The HESR cannot support a traditional accumulation system which is based on a ring with large momentum acceptance. The HESR has a momentum acceptance of $\Delta p/p = \pm 0.25\%$ which is less than twice the momentum spread of the bunch from the CR. On the other hand, the circumference of the HESR is more than double the circumference of the CR. Therefore, a longitudinal accumulation scheme is much more favorable. In addition, the HESR is equipped with a stochastic cooling system and a barrier bucket rf system, thus no significant additional investment is required [4]. It is clear, however, that accumulation in the HESR will reduce the luminosity for experiments with stored antiprotons. A similar scheme for the accumulation of high intensity heavy ion beams is proposed in the frame of the NICA project [5]. At Fermilab, barrier buckets (BB) are being used in many beam manipulations, in particular in combination with stochastic cooling [6]. Efficient antiproton accumulation using the h=1 rf system and stochastic cooling was first demonstrated in ICE [7].

As the usefulness of stochastic cooling in combination with BB is not obvious due to increased coherent signals originating from the time structure of the beam, a proof of principle experiment was proposed. This requires the availability of injected bunches in the receiving storage ring with fast kicker injection, a stochastic cooling system and a BB rf system. All these requirements are met by the ESR [8] storage ring at GSI with the synchrotron SIS18 as injector. Similar accumulation experiments in combination with electron cooling have been performed before [9]. From these experiments two serious limitations are well known. Firstly, the timing of the injection kicker of the ESR is very critical, in particular because of the small ring circumference and the resulting relatively short revolution time. Secondly, the ESR is not equipped with a dedicated BB system, the modified ESR acceleration cavity can provide a maximum voltage of 120 V in the BB mode. Nevertheless, with these known limitations the ESR is useful to study the accumulation process and allows a comparison of experimental observations with the computer codes used to predict the performance of accumulation in the future scenario in the HESR. In particular, this will give better confidence in the estimated parameters of the systems involved in the accumulation process.

EXPERIMENTAL PROCEDURE

In this frame, different longitudinal beam accumulation schemes in combination with stochastic cooling have been investigated by experiments and benchmarked by simulations [10].

The first method uses short BB pulses provided by a broadband rf system [11]. In the moving BB scheme, two sinusoidal BB pulses are applied. 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 wave barrier pulses of opposite sign. The resulting stretched rf potential separates the longitudinal phase space into a stable and an unstable region. After injection into the unstable region (potential maximum), the particles are pushed by cooling to the stable region. After some time the unstable region is free again for injection.

The second method uses a h=1 rf system for bunching (adiabatically) of the circulating beam and injection of a new bunch onto the unstable fixed point. Then, the voltage is decreased (rather fast in order to avoid dilution of the new bunch) to let the beam debunch. In both schemes, continuous application of stochastic cooling counteracts heating of the stack during the rf compression and merges the stack with the freshly injected bunch. The required rf voltage for the longitudinal beam compression is moderate since the momentum spread of the cooled stack is small (of the order of a few times 10^{-4}). However, as shown below, the maximum available voltage of 120 V of the present BB cavity was a limiting factor. The cooled stack is repeatedly subjected to the same procedure until an equilibrium between beam losses and injection rate is reached.

Both options have been tested in the ESR under the same conditions. The experiments were performed with a $^{40}\mathrm{Ar}^{18+}$ beam at 400 MeV/u injected from the synchrotron SIS. The SIS and ESR rf systems were synchronised to operate at f_{rf}=1.97 MHz, 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 260 ns long (100 ns rise and fall time, 60 ns flattop), thus affecting about half of the ESR circumference. Well-controled and precisely synchronised kicker pulses of all three injection kicker modules were essential for the success of the experiment. The total time of one revolution period (T_{rev}=507 ns) had to be shared among the injected beam, the BB pulses (sinusoidal of period T_B=200 ns) and the stacked beam. The short injection kicker pulse restricted the injection efficiency. At each injection from the SIS the ESR received on average 20μA of beam current (3.5 × 10^6 ions) in a pulse with a FWHM of about 60 ns (see Figs. 2 and 3). In the HESR, which has a larger circumference, the revolution period for 3 GeV antiprotons is 2 μs, thus a longer kicker pulse can be used, permitting the injection of the single bunch of precooled antiprotons from the CR.

The maximum height of the rf barrier δ_B is given by the usual formula for a sinusoidal rf pulse

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

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 $h = T_{rev}/T_B \approx 2.5$ is defined. Hence, at the same voltage the confining potential of the BB system is $\sqrt{2.5}$ lower than for the h=1 rf.

The time between two successive injections, i.e. the stacking cycle time, depends on the cooling process. The ESR stochastic cooling system [12] is designed for a particle velocity corresponding to 400 MeV/u beams. Cooling in all three dimensions is provided within the band from 0.9 to 1.7 GHz. Measurements of the momentum spread by Schottky noise diagnostics showed that the injected beam had a momentum spread (full width at baseline) of 1.3 $\times 10^{-3}$ and was stochastically cooled down to 6 $\times 10^{-4}$ within 13 s.

STACKING WITH FIXED BARRIER BUCKETS

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.1).

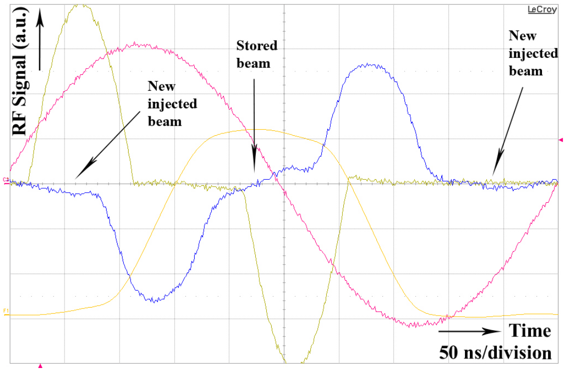

Figure 1: Realisation of fixed BB. Measured rf voltage pulse (blue line) and its potential with opposite sign (orange line). Applied BB voltage (yellow line). Carrier rf wave at h=1 used to synchronise the SIS and ESR rf systems (magenta line).

Fig. 2 shows the $^{40}\mathrm{Ar}^{18+}$ signal measured in the ESR beam position monitor during the stacking and illustrates the experimental procedure. The after-pulses of the kicker pulse in Fig. 2 are due partly to real jitter and mostly to cable reflections on the signal line. Because of the jitter, the kicker pulse overlaps in time with the tail of the stack. This leads to transverse heating of the particles in the stack and to beam loss from the stack at every injection.

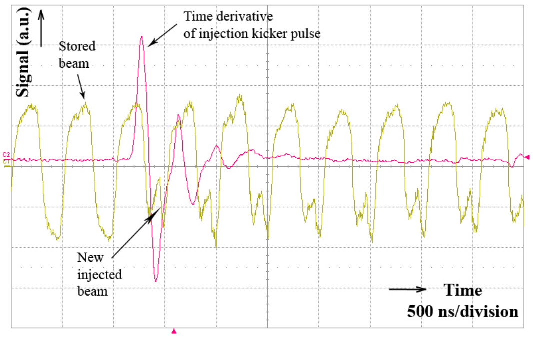

Figure 2: Signals (arbitrary units) of the stored beam at saturation intensity of 0.25 mA and of the injected bunch. The measured time-derivative of the injection kicker pulse is also shown but is not correlated to the beam signal because of different cable delays. The difference between the max. and the min. of the kicker pulse corresponds to ∼3 flattop=180 ns.

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 losses induced to the tails of the stack by the jitter of the kicker at every injection were observed as follows: After reaching the saturation intensity, the transfer of beam from the SIS was stopped, but operation of the ESR injection kicker continued (Fig. 3).

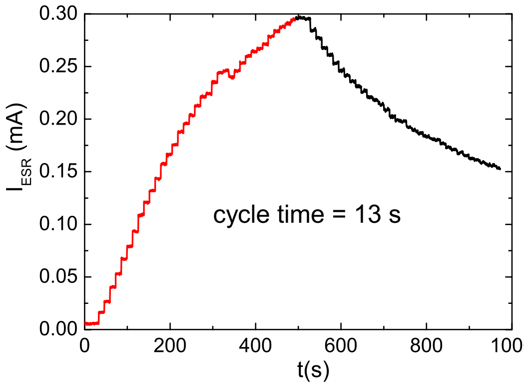

Figure 3: Stacking by fixed BB and antistacking, i.e. kicker operation without injection of new beam, in the ESR. Stochastic cooling continuously applied. A beam current of 0.4 mA corresponds to 7×10^7 $^{40}\mathrm{Ar}^{18+}$ ions at 400 MeV/u in the ESR.

In the present case, the main reason for the saturation of the stacked beam current is the following: Within the short time T_{rev}=507 ns, some overlapping of the BB pulses and of the kicker pulse with the tails of the stacked beam could not be avoided. As the stored beam current and the corresponding bunch length of the stack increase, the particle losses from the stack due to these overlaps also grow, until a saturation is reached.

Fig. 4 shows a qualitative investigation of the cooling performance. Fig. 5 illustrates the importance of good horizontal cooling (in addition to longitudinal and vertical). Without horizontal cooling the horizontal emittance grows because of the disturbance from (i) the injection kicks and (ii) the longitudinal correcting kicks since the longitudinal stochastic cooling kicker is located at high dispersion in the ESR (D ≈ 6 m).

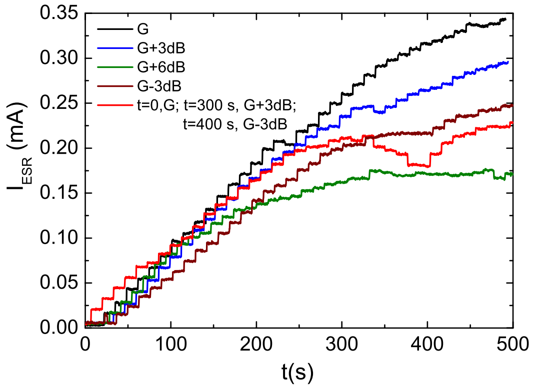

Figure 4: Stochastic cooling performance during stacking with fixed BB, for different gain values relative to an initial value G.

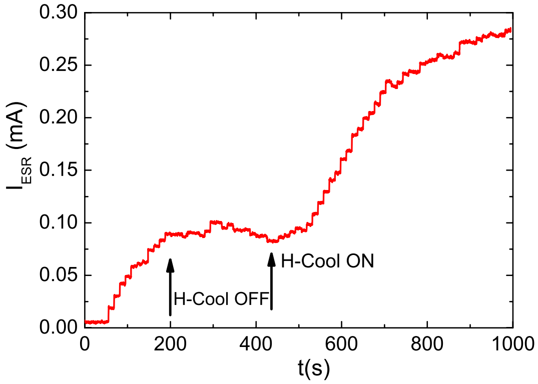

Figure 5: Role of the horizontal stochastic cooling during stacking with fixed BB.

PROCEDURE WITH MOVING BARRIER BUCKETS

In this scheme, two BB pulses are adiabatically introduced into the cooled coasting beam. One stays stationary while the other is shifted in phase during 0.9 s to compress the beam. At t ≈ 1.7 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 bucket height $2\delta_B$= 5 $\times 10^{-4}$ was not sufficient to maintain the cooled stack with $\Delta p/p = 6 \times 10^{-4}$ during the compression (although the moving of the buckets was adiabatic w.r.t. the synchrotron motion of the stack, which occurs at a rate $\Delta f/f = \eta \Delta p/p \approx 2 \times 10^{-4}$). Thus, particles from the stack remained in the gap, got lost at every new injection and no accumulation could be observed. Application of additional electron cooling (at electron beam density of 6×10^6 cm^{-3}) further reduced the momentum spread of the stack, making accumulation possible (Fig. 6).

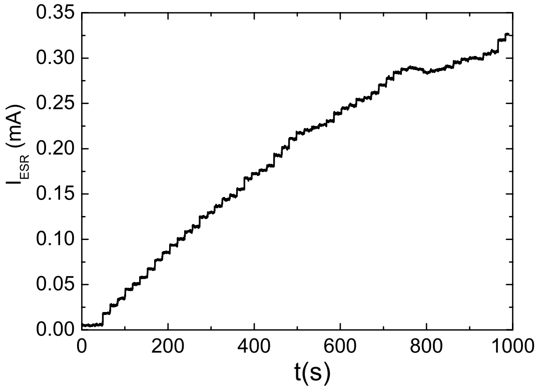

Figure 6: Stacking in the ESR using moving BB. Stochastic and electron cooling continuously applied.

STACKING WITH THE *H*=1 RF

In this scheme, the standard ESR rf cavity provided higher voltage and thus higher saturation instensities have been reached. Two cases of rf manipulation have been tested, yielding qualitatitevely similar results: (i) continuous application of the h=1 sine wave i.e. continuous cooling into the bucket and multiple injections onto the unstable fixed point; (ii) isoadiabatic bunching of the beam within 0.2 s, holding the rf voltage constant for 1.3 s in order to cool into the bucket and receive the new bunch on the unstable fixed point, abrupt (within 50 μs) switching-off the rf voltage to merge the two beam components. Fig. 7 shows the accumulation curves obtained with the procedure (ii).

The option of stacking with the h=1 rf may be advantageous since a longer injection kicker pulse can be used than in the BB schemes. This guarantees high injection efficiency if the incoming bunch is long w.r.t. the ring circumference.

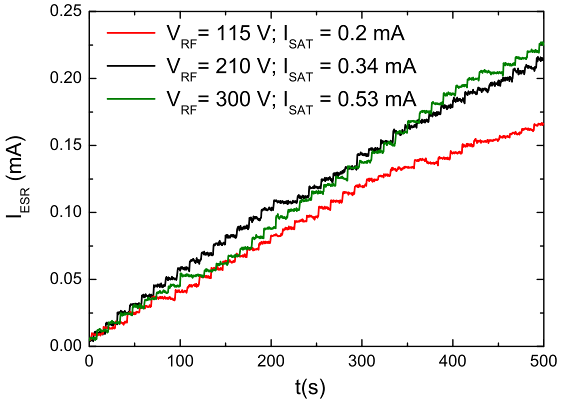

Figure 7: Stacking in the ESR using the h=1 rf. Saturation intensity reached for different peak voltages.

CONCLUSIONS AND OUTLOOK

If the revolution period of the beam is long, e.g. for lower beam velocity or for a long ring like the HESR, the injected bunch, the stack, the BB pulses and the injection kicker pulse can be well-separated. Then, the accumulation will continue until the momentum spread of the stack as determined by the equilibrium between stochastic cooling and intrabeam scattering fills the available rf bucket height. An additional limiting factor is the onset of instabilities. These effects have been quantitatively studied in the case of stacking combined with electron cooling in the ESR [13].

For realistic future operation of the longitudinal stacking mode in the ESR, it is planned to install a new dedicated BB cavity, providing a voltage up to 2 kV. Depending on the injection energy, stochastic or electron cooling will support the stacking. Thus, the intensity of low-abundant rare isotope beams can be effectively increased, as requested by in-ring experiments.

The experimental results at the ESR demonstrate the principle and feasibility of the stacking methods. They indicate how the expected luminosity in the HESR will be a trade-of between accumulated intensity, duty cycle and phase space quality. In this respect, flexibility in the choice of the stacking method should be foreseen. These results can be extrapolated to set or confirm the requirements for the HESR systems, namely, (i) faster stochastic cooling or cooling of higher number of particles (larger bandwidth), (ii) a BB cavity with 2 kV peak voltage with the option to operate as h=1 rf system, (iii) an adjustable injection kicker pulse and (iv) powerful beam diagnostics.

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