A NEW METHOD FOR BEAM STACKING IN STORAGE RINGS*

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Abstract

Recently, I developed a new beam stacking scheme for synchrotron storage rings called "longitudinal phase-space coating" (LPSC). This scheme has been convincingly validated by multi-particle beam dynamics simulations and has been demonstrated with beam experiments at the Fermilab Recycler. Here, I present the results from both simulations and experiments. The beam stacking scheme presented here is the first of its kind.

INTRODUCTION

Considerable progress has been made over the years to develop improved methods for beam stacking in synchrotron storage rings [1]. The methods of beam stacking are broadly categorized into a) *box-car* stacking [2], b) transverse and longitudinal phase-space painting (LPSP) [3] and c) momentum stacking and cooling [4]. The most of these methods use resonant rf systems and have their merits and limitations. The Recycler Ring at Fermilab [5], an 8 GeV antiproton storage ring, uses *barrier rf* technology [6] in all of its beam manipulations, unlike any storage rings in the world. Therefore none of the methods of beam stacking mentioned above can be used in the Recycler Ring without major rf modifications.

Currently, the Recycler is used as the primary antiproton depository at the Fermilab accelerator complex. During normal antiproton stacking, $\sim 20 \times 10^{10}$ antiprotons with total longitudinal emittance (LE)<13 eV s are extracted from the Fermilab Accumulator Ring and injected into the Recycler. The new beam is added to the initial *cold beam* which resides in another rectangular barrier bucket in the Recycler. This sequence of beam transfer is repeated several times a day until the Recycler stack has enough antiprotons to fill the Tevatron for collider operation. The entire stack of the Recycler is cooled using electron cooling and stochastic cooling methods between the antiproton transfers.

Over the past several years, a number of improvements have been made in antiproton stacking schemes [7] in the Recycler. Recently, we implemented a scheme which involves the *morphing* of barrier rf pulses [8]. In this scheme, the two closely spaced barrier pulses that define the boundary between the newly injected beam and the initial (cold) beam are made to disappear by reducing their widths slowly and symmetrically keeping the extent of the unstable region between them zero. This minimizes emittance dilution due to merging of two super bunches. The emittance growth observed by this method is as low as about 15%. Since the implementation of this technique,

we have stacked and cooled in excess of 4.3×10^{12} antiprotons in the Recycler. However, the disadvantages of the methods are that a) the initial beam is significantly disturbed every time a new beam is added and b) the momentum spreads of the new beam and that of the initial beam have to be matched each time before merging. In the case of multiple beam transfers, the overall emittance growth is as high as 50%.

In this paper I present a new scheme of beam stacking "longitudinal phase-space coating" [9]. The 6D emittance of the original beam can be kept unchanged for any number of transfers the storage ring allows and the emittance growth for the rest of the beam is minimal. This novel technique depends crucially on the availability of barrier rf system. The beam stacking illustrated here is carried out using rectangular barrier buckets.

PRINCIPLE OF LPSC

The method of LPSC explained here is different from LPSP explained in the literature [3]. LPSC can be viewed as the reverse of "longitudinal momentum mining" [10]. The principle of LPSC is illustrated schematically in Figure 1 with the assumption that the beam energy is below the transition energy of the synchrotron.

The principal goal of the LPSC is to coat the injected beam on the 2D-surface of the initial beam. The coating takes place in $(\Delta E, \Delta t)$ -space.

The LPSC comprises of four steps. In the first step, the original beam is captured in a barrier bucket made up of rf pulses "1" and "2" as shown in Figure 1(a). At this stage the bucket area is significantly larger than the beam phase space area. Next the beam is captured in a smaller bucket (made of barrier pulses "3" and "4" as indicated in Figure 1(b)) with area exactly equal to that of the initial beam, given by,

$$\varepsilon_m = \Delta T \Delta E_m + T_0 |\eta| \Delta E_m^{\ 3} / (6\beta^2 E_0 e V_m)$$

where ΔT, ΔE_m, T_0, η, E_0, and V_m are barrier separation of the mini-bucket, bucket height of the mini-bucket, beam revolution period, slip factor of the storage ring, beam synchronous energy and the amplitude of the barrier pulse, respectively. e is the charge of an electron and $\beta = v/c$ for the beam. Thus, there are two barrier buckets, one inside the other, with the inner bucket containing the entire beam. This implies that the original beam is kept at a lower potential relative to the newly injected beam so that the bottom of the potential of the new beam is always level with the top of the original beam as shown in Figure 1(b). The third step involves coating the top of the original beam with the new beam by removing barriers "2" and "5" adiabatically (by either lowering the voltage or by morphing). The final step is to compress the beam adiabatically by bringing barrier pulse "6" to the position

of "2" as shown in Figure 1(d) so that more beam can be injected. With this approach, one can completely eliminate the LE growth.
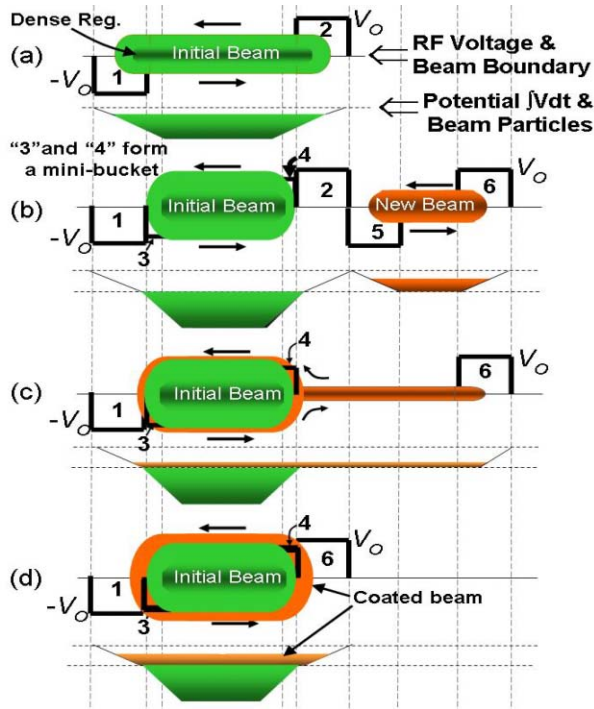

Figure 1: Schematic view of beam stacking by LPSC. The phase space and potential diagrams are shown for every stage of stacking: (a) original beam, (b) after capturing the original beam in a mini-barrier bucket and injection of a new beam, (c) first stage of coating of the new beam on top of the original beam and (d) after coating. The voltage wave forms (solid lines) are also shown in each case. The horizontal line indicates time axis.

One can think of many variations of the method explained above. For example, only the dense region of the initial beam can be captured and coat the new beam after mixing with the rest or/and increase the height of the mini-bucket every time after coating the new beam to capture a part of the new beam, etc.

DEMONSTRATION

We have demonstrated the LPSC scheme described above in the Fermilab Recycler. The Recycler operates below the transition energy (γ_T = 21.6) and has T_0= 11.12 μsec. The antiproton/proton beam can be stacked and stored azimuthally using barrier buckets made of rf pulses of 2 kV each. The testing of the LPSC has been carried out in two steps: (i) a computer simulation using ESME [11] with the Recycler machine parameters to validate the concept and facilitate the experiment, and (ii) experimental demonstration of the technique.

The computer simulations using an ideal beam particle distribution showed all of the features of the stacking process. For example, for particles populated with a

parabolic or an elliptical distribution in the ΔE–coordinate and a random distribution in the Δt–coordinate, no emittance growth is observed. But with a Gaussian distribution in the ΔE–coordinate, a small emittance growth <5% was observed.
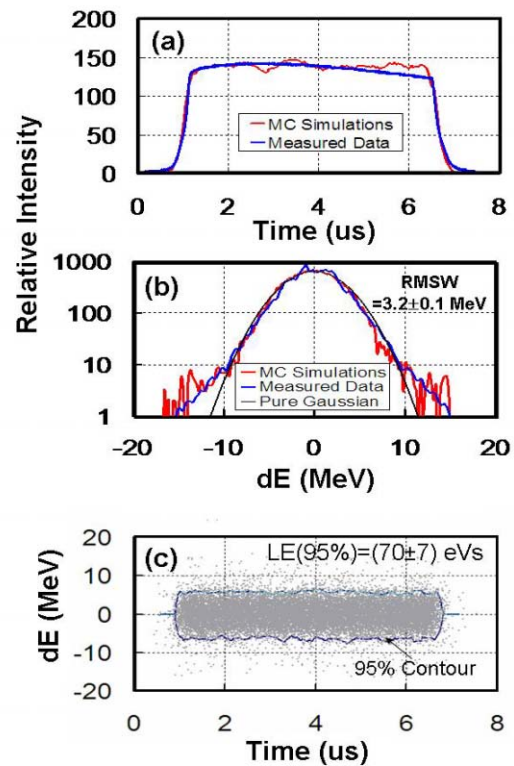

Figure 2: Comparison of MC simulation with the measured data for the initial beam before any coats. The denser region of the initial beam occupying about 66 eV s of the longitudinal phase space is captured using a mini-barrier bucket. The rest are in the bigger bucket. (a) Wall current monitor, (b) Schottky detector data (The dark trace is Gaussian distribution with standard deviation = measured RMSW). The blue and red traces are, respectively, experimental data and MC simulations (c) The MC generated longitudinal phase-space distribution of the beam with 95% contour.

The experiments were carried out in the Recycler using proton [9] as well as antiproton beams. Here I illustrate the scheme with an experiment done using the antiproton beam.

Initial beam of about 2.6×10^{12} antiprotons were stored in a rectangular barrier bucket (length ~5.9 μsec, barrier pulse width~ 0.9 μs each and barrier pulse amplitude ~1.8 kV) cooled to a LE ~ 70±7 eV s (95%). The available bucket area and height for this barrier bucket were ~250 eV s and 17.5 MeV, respectively. Then, a mini-bucket of area ~66 eV s, (V_0 ~0.72 kV, pulse width~0.25 μsec and ΔT~5.4 μsec) was opened to capture about 94% of the initial beam. The initial line-charge distribution and the

Schottky data (energy distribution) are shown in Figures 2(a) and (b), respectively (blue traces).

Next, the new beam was added to the initial stack in three successive injection with about 7±1, 8±1 and 7±1 eV s (a total of 22±2 eV s) with 14×10^{10}, 9×10^{10} and 5×10^{10} antiprotons each, respectively, using the LPSC method. The data taken at the end of all transfers are shown in Figures 3(a) and (b).
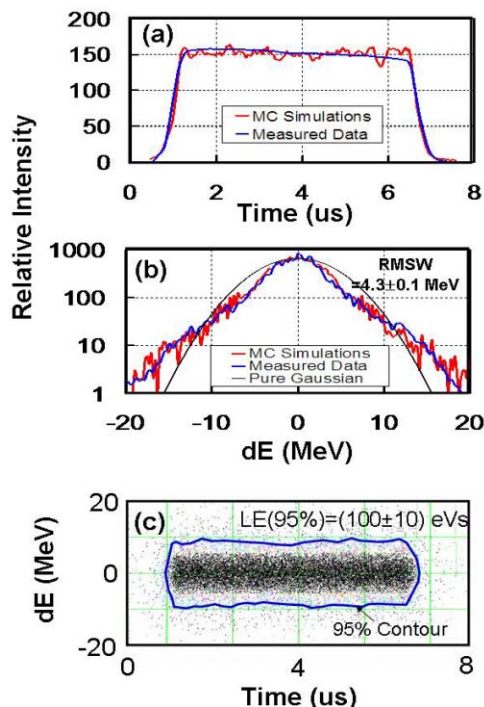

Figure 3: Comparison of MC simulation with the measured data for the beam after coating three times. About 94% of the initial beam occupying ~ 66 eV s is still residing in the mini-bucket. The final emittance measured by using the MC method is also shown. The descriptions for three plots and the traces are the same as in Figure 2.

The barrier pulses used for this experiment were not exactly rectangular in shape. Hence, the LE cannot be estimated using standard analytical formulae (see the 2nd ref. of [9]). Consequently, I used a beam Monte Carlo (MC) method [12] to estimate the LE at different stages of stacking.

The MC calculations were carried out using ESME within the realm of single particle beam dynamics. The study shows that the energy distributions of the antiproton beam cooled using e-cool and stochastic cooling deviate from any standard distributions. The beam particle distribution in ($\Delta E,\Delta t$) –space from the MC calculations was fine-tuned until projections of the final distribution on Δt and ΔE- axis converge to the corresponding wall current monitor and Schottky data, respectively. The red curves in Figures 2(a) and 2(b) show MC predictions for the initial beam.   The difference between root mean square widths (RMSW) for the experimental Schottky spectrum and the MC predicted energy spectrum   is <3%. The LE (95%) for the initial beam is estimated from the (converged) MC result by drawing "95% contours" which embed 95% of all the particles in the ($\Delta E,\Delta t$) –phase-space distribution (see Figure 2(c)). Thus, we found LE(initial)= 70±7 eV s. From similar analysis for the beam after three coats gave LE(final)= 100±10 eV s(see Figure 2(c)). This implies that there is <10% LE growth after adding ~22 eV s to the initial beam.

In summary, I have developed and validated a novel beam stacking method in hadron storage rings. The method was studied using multi-particle beam dynamics and was successfully demonstrated in the Fermilab Recycler. With this technique the longitudinal emittance dilution was <10% during beam stacking.

As a note, I was able to produce longitudinal hollow beams as one of the spin-offs of these experiments, which may have broad applications in beam dynamics studies. Further, an intermediate step of the technique explained here, (see Figure 1(c) which was called *compound bucket* in ref. 13) led to significant research in improving beam cooling in the Recycler.

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