ANTIPROTON STACKING AND UN-STACKING IN THE FERMILAB RECYCLER RING*

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Abstract
The Fermilab Recycler Ring (RR) is intended to be used as a future antiproton storage ring for the Run II proton-antiproton collider operation. It is proposed that about 40mA of antiproton beam from the Accumulator Ring will be transferred to the Recycler once for every two to three hours, stacked and cooled. This operation continues for about 10 to 20 hours depending on the collider needs for antiprotons. Eventually, the cooled antiproton beam will be un-stacked from the Recycler and transferred to the Tevatron via the Main Injector. We have simulated stacking and un-stacking of antiprotons in the Recycler using multi-particle beam dynamics simulation code ESME [1]. In this paper we present results of these simulations.

INTRODUCTION

Fermilab has planned to use the Recycler [2] as the main antiproton storage ring in future. The primary goal of the Recycler is to stack in access of 200E10 antiprotons, cool and transfer to the Tevatron for proton-antiproton collider operation. The stacking of the antiprotons in the Recycler is carried out on several transfers over 10-20 hrs by extracting them from the Accumulator Ring. Every transfer takes place whenever the stack size in the Accumulator Ring is above about 40E10. As and when it is needed, the antiprotons in the Recycler will be un-stacked in the form of thirty-six 2.5MHz low emittance intense bunches and sent to the Tevatron via the Main Injector. Both stacking and un-stacking of the antiprotons in the Recycler Ring involve complicated sequences of rf manipulations like de-bunching/re-bunching, squeezing/un-squeezing, cogging, merging/slicing of the beam. These rf manipulations should be carried out in adiabatic fashion to retain emittance.

In this paper we present longitudinal beam dynamics simulations for the stacking and un-stacking of the anti-protons in the Recycler. The simulations have been carried out with an emphasis on preservation of longitudinal emittance at every stage of the rf manipulation. The simulations have been carried out using a 2D-multi-particle beam dynamics Monte Carlo code ESME [1].

The Recycler is an 8 GeV proton/antiproton synchrotron and its lattice is very similar to that of the Main Injector [3]. The *slip factor* of the Recycler is about -0.0086 and the harmonic number h = 28 (for 2.5MHz rf system). All beam manipulations in the Recycler are carried out using a broad-band rf system [4] which can produce barrier buckets of any shape. We use barrier buckets made of rectangular rf pulses (max. pulse height=2 kV and width = 0.908μsec) to store the beam. An efficient rf control system has been developed [5] to perform all of the rf manipulations. Presently, the Recycler is being commissioned using the proton beam from the Fermilab 8 GeV Booster. We also had several antiproton stores in the Recycler.

SIMULATIONS

The simulations were carried out in two steps. The first step involves an optimization of individual process like de-bunching of the 2.5MHz bunches in a barrier bucket, re-bunching in to 2.5MHz buckets, squeezing, etc. For example, to study the de-bunching process a train of four 2.5MHz bunches are injected in to matched buckets of the Recycler which are bounded by a barrier bucket of pulse gap of 1.59 μsec. Next, we optimize the rate at which the 2.5MHz bucket is brought down from 2kV to 0.0kV and how it is brought down – suddenly, linearly or adiabatically. As we expected, by turning off the 2.5MHz rf voltage suddenly gave largest emittance growth. On the other hand, a truly adiabatic process is less practical. An iso-adiabatic de-bunching is developed by combining three linear processes in succession. At present, in the Recycler, we adopt a similar de-bunching technique by bringing down the 2.5MHz rf voltage from 2 kV to 1 kV in 5 sec, from 1 kV to 0.5 kV in the next 5 sec and take 10 sec to go down from 0.5 kV to 0.0 kV. Thus we take about 20 sec for the entire de-bunching process. A similar, but reverse procedure is adopted for re-bunching. Our simulations suggested that we can reduce the de-bunching and re-bunching time at least by a factor of two in the operation without any emittance dilution by bringing down the rf voltage from 2kV to 1kV in 2 sec, 1kV to 0.5kV in next two second and 0.5kV to 0 kV in the final 4 sec. These simulation results have been verified using beam measurements.

Figure 1 shows simulated wall current monitor data (with a relative normalization) and a data from a beam measurement. The figure 1(a)-(c) show a case for four 2.5MHz bunches of beam in the Recycler de-bunched in 8 sec and re-bunched in 8 sec. The corresponding wall current monitor data is shown in figure 1(d). The beam data show that the bunch lengths before and after de-bunching are the same within a few percent.

Similar simulations are performed for different processes to establish optimum operational conditions.

The second step involves the simulations of the entire process of stacking and un-stacking of the beam.

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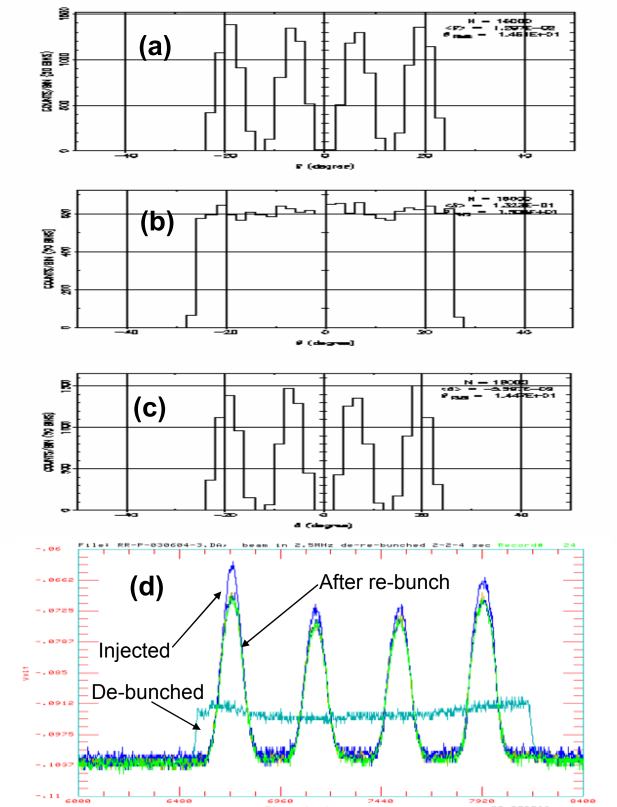

Figure 1. Results of ESME simulations of wall current monitor data. (a) The beam at injection in the 2.5MHz buckets, (b) De-bunched in 8 sec, (c) Re-bunched in 8 sec as explained in the text. (d) Wall current monitor data taken during a beam experiment for similar conditions. The measured bunch lengths before de-bunching and after re-bunching are essentially the same.

Stacking of Pbars

Figures 2 and 3 show the simulations of the entire stacking sequence for three transfers. Fig. 2(a) shows the injection of four 2.5MHz bunches into the Recycler. These bunches are de-bunched and are squeezed symmetrically in a barrier bucket by moving the upstream and the downstream barrier pulses towards the center of the barrier bucket in about 5.25 sec. We used a linear cog rate of the barrier pulse=4.89deg/sec. The phase-space distribution of the beam particles and its projection on the θ-axis after squeeze are shown in Fig. 2(e) and 2(f), respectively. Before the injection of the new group of four bunches the squeezed beam bunch is moved to a new location using the same cog rate (see figure 2(g)).

Similar procedure is repeated for the 2nd and 3rd transfers. A special care is taken while merging the new transfer with the old stack. Here we have investigated two methods of merging. In the first method, we simply cog the second set of fully squeezed bunch towards the old stack. As the head of the moving bucket interferes with the tail of the old bucket, the –ve and +ve barrier pulses start canceling one another at the same time they produce an increasing non-stable region between them which produces a void in the phase-space area of the final stack. In the second method, the merging of the stacks involves two steps: 1) Bring two buckets as close as possible and reduce the barrier pulse heights adiabatically to zero voltage as shown in figure 3(a) and (c), 2) Squeeze the final stack to get proper dp/p. The simulation suggested that the 1st method introduces a hallow in the middle of the (ΔE, Δθ)-space of beam particle for the final distribution resulting in a small emittance dilution. On the other hand the 2nd method gives rise to smaller emittance growth.

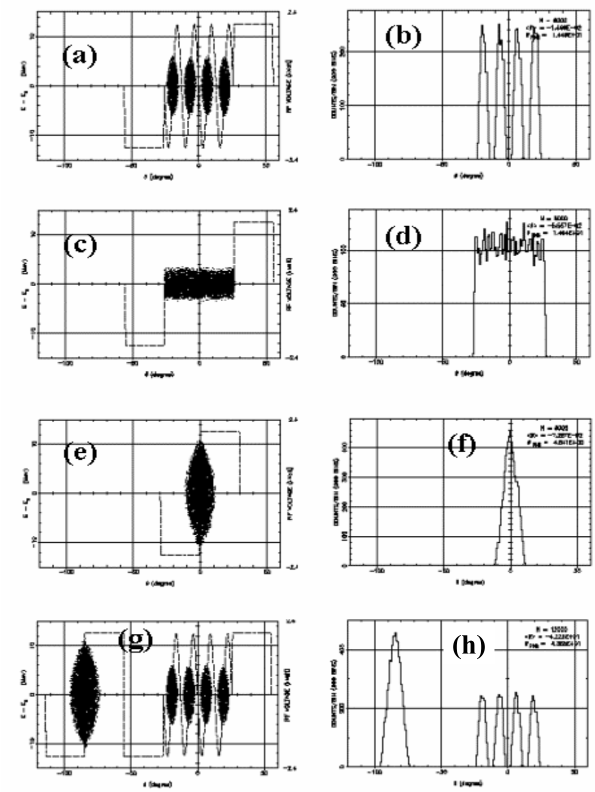

Figure 2. ESME simulations of the beam stacking in the Recycler. The figures (a), (c), (e) and (g) show (ΔE, Δθ)-phase space distributions of beam particles. The figures on right show their projections on θ – axis (equivalent time coordinate).

In our simulations, we have used a rate of 400 V/sec for reducing the barrier pulse voltage in figure 3(c) and after merging of new transfers the final stack is squeezed by 41.6deg to get dp/p for final stack to be same as that of bunches shown in figure 3(a). Before injecting the next group of four 2.5MHz bunches the final stack of the beam is cogged by 71degs so that the new injection barrier bucket can be grown at the same azimuthal location of the Recycler. We find that stacking of a new injection can be performed in about 33 sec with out any emittance growth (compare this with 105 sec scenario which is in use at the Recycler). Note that, the simulation does not include any rf noise or any other un-wanted mechanism which would give rise to emittance dilutions.

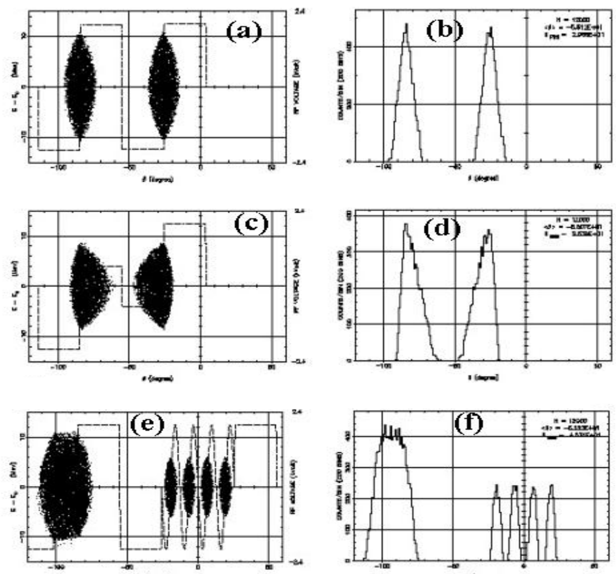

Figure 3. ESME simulations to illustrate a way of merging two stacks (particularly see (c) and (d)). (e) and (f) illustrate a new injection.

Unstacking of Antiprotons

For the simulations of unstacking of the beam we start with the final distribution produced from the previous stacking simulations. The sequences are essentially reversed. The entire process of beam unstacking is shown in Figures 4 and 5. Simulations predicted <5% emittance growth.

In summary, we have carried out simulations for both stacking and un-stacking of antiprotons in the Recycler to establish better operating conditions. We find that the total time required for a beam stacking sequence is about 33 sec, which is about a factor of three smaller than the present operating scenario in use. Special attention should be given to cog rate of the barrier pulses and buckets. A cog rate of 4.89 deg/sec gives <5% emittance growth. We plan to test these results using the beam in the Recycler.

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REFERENCES

* Work supported by the Universities Research Association, Inc., under contract DE-AC02-76CH03000 with the U.S. Department of Energy.

[1]. J. MacLachlan, ESME modified to handle beam dynamics in barrier buckets (1996), (private communications

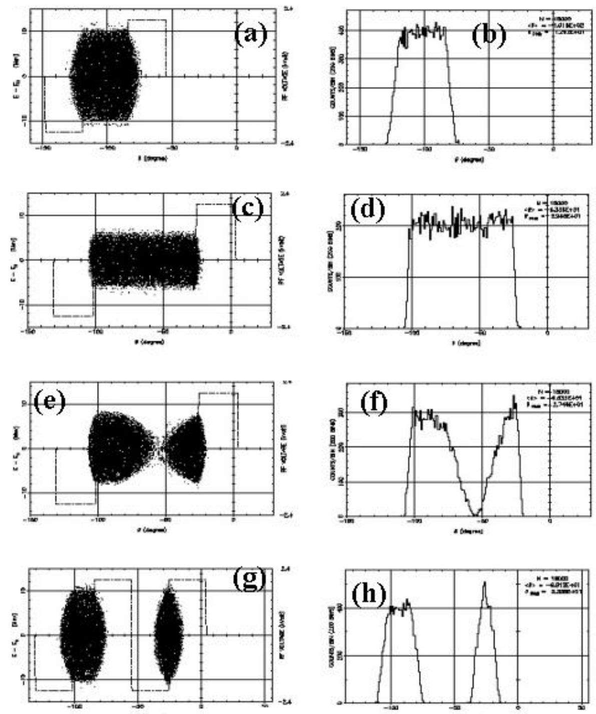

Figure 4. ESME simulations illustrating the beam un-stacking sequences.

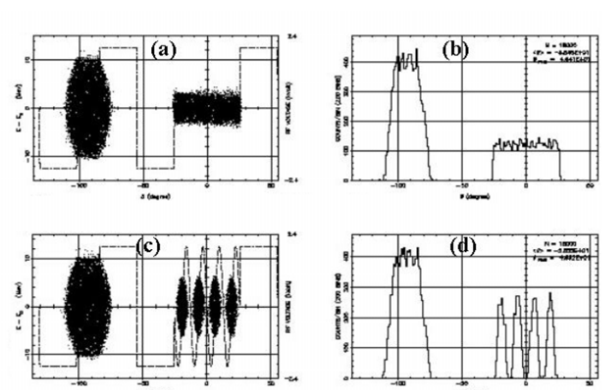

Figure 5. ESME simulations illustrating the beam un-stacking sequences.

[2] "The Fermilab Recycler Ring Technical Design Report" G. Jackson, FERMILAB-TM-1991 (1996).
[3] "The Fermilab Main Injector Technical Design Handbook" Fermilab Internal Document (1994)
[4] J.E. Dey and D.W. Wildman, IEEE, Proc. the 1999 Part. Accel. Conf. New York, NY, 869, 1999).
[5] B. Chase and K. Meisner (private communications, 2003).