COOLING IN A COMPOUND BUCKET

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Abstract

Electron cooling in the Fermilab Recycler ring is found to create correlation between longitudinal and transverse tails of the antiproton distribution. By separating the core of the beam from the tail and cooling the tail using "gated" stochastic cooling while applying electron cooling on the entire beam, one may be able to significantly increase the overall cooling rate. In this paper, we describe the procedure and first experimental results.

INTRODUCTION

Presently, antiprotons in the Fermilab Recycler ring [1] are stored between rectangular RF barriers and are cooled both by a stochastic cooling system in the full duty-cycle mode (primarily in the transverse planes) and by a DC electron beam (primarily in the longitudinal phase-space). As the number of antiprotons, N_p, in the Recycler increases, the rate of stochastic cooling decreases according to $1/N_p$ [2]. In the case of electron cooling, the cooling strength does not depend on N_p, but it is significantly stronger on the core particles as compared to that in the tail region of the 6D-phase-space [3]. These properties combined result in a formation of a dense core but long tails and a poor beam lifetime. In this paper, we propose a technique of separating core and tail particles to combine advantages of both cooling techniques in the Recycler.

COMPONENTS OF THE SCHEME

Tail correlation

Measurements in the Recycler have shown [4] that the longitudinal cooling force quickly drops at a radial offset inside the electron beam of ≤1 mm. Typical rms radius of newly arrived antiprotons from the Accumulator ring is about 2 mm. Consequently, particles with large transverse actions are only weakly affected by the electron cooling. Eventually, the tail of the momentum distribution is populated primarily with particles of large transverse action (see Fig.3 in Ref. [4]). Note that this feature is not observed in an antiproton beam cooled by stochastic cooling alone.

Compound bucket

The effect of tail correlation can be used for longitudinal separation of the core and tails by application of a so-called compound bucket. The scheme of the compound bucket is illustrated in Fig.1. Normally, the beam is stored between two rectangular barriers, labeled as #6 and #7 in Fig.1 in accordance with the internal Recycler system. In

the compound bucket, two lower-width "mini-barriers"#3 and #4 create an additional step in the effective RF potential, so that only particles with a large energy offset travel between barriers #4 and #7. Below we refer to this area as the tail region.
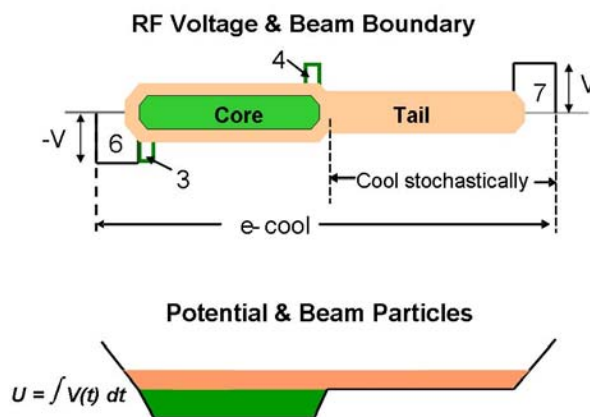

Figure 1. Scheme of the compound bucket. Horizontal axis shows the longitudinal phase (usually expressed as a time delay from the arrival of the bunch head) and corresponds to one revolution period. The top plot shows positions of RF barriers and longitudinal phase space of antiprotons (with vertical axis representing energy deviation). The bottom plot pictures corresponding effective RF potential.

Momentum coating

The concept of the compound bucket was first introduced in Ref. [5] for the momentum coating injection scheme.
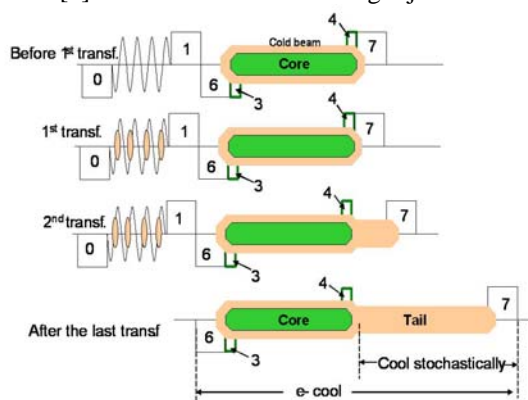

Figure 2. Injection with the compound bucket. RF forms and momentum distributions are shown for the case of two transfers.

In this scheme (Fig.2), the cold beam in the Recycler ring is kept between mini-barriers #3 and #4 while the new particles arriving from the Accumulator are injected in

between barriers #0 and #1 at the energy corresponding to the potential between main barriers #6 and #7 so that they "coat" the cold beam in the energy-phase space.

Gated stochastic cooling

In addition to operation in the full duty-cycle mode, the Recycler stochastic cooling system can be turned on for a part of the revolution period so that cooling is applied only for a portion of the circulating beam [6]. Below we will refer to such timing as "gating". In the described scheme, the transverse stochastic cooling system is gated only on the region between barriers #4 and #7. The height of the mini-barriers is chosen so that the density of antiprotons in the tail is noticeably lower than that in the core region. Hence, the stochastic cooling can be applied with a high gain that significantly speeds up transverse cooling where it is needed the most, i.e. for the newly injected antiprotons with large transverse emittances.

COOLING IN THE COMPOUND BUCKET

Figure 3 shows schematically the idea of cooling in the compound bucket. The goal is to put all antiprotons into the phase-space core (area A) as fast as possible. Electron cooling effectively drags particles with low transverse action from area D. Antiprotons in area C are subject to the gated stochastic cooling that squeezes them into area D. Intra-beam scattering, scattering on the residual gas, and other mechanisms present at regular operation continuously heat the core particles (we refer to this as natural heating). Transverse natural heating pushes them to area B, while longitudinal heating in the area between barriers #3 and #4 moves these antiprotons from area B to C. The latter move needs to be fast enough to avoid losing antiprotons from area B due to the transverse diffusion of all sorts. Because the natural heating rate was found to be too low, an external longitudinal heating is applied, so that eventually all particles spend most of their time in area A by completing the cycle shown in Fig. 3.
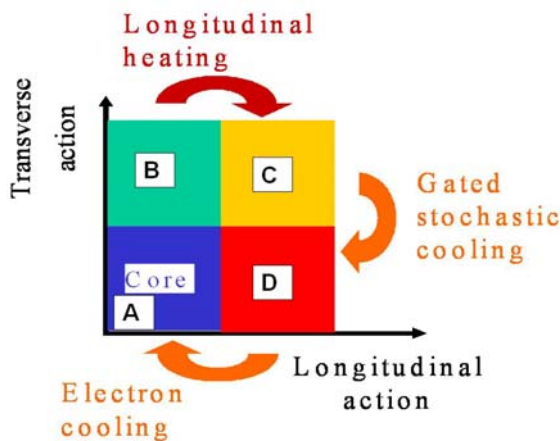

Figure 3. Illustration of cooling in compound buckets.

DIAGNOSTICS

Several types of diagnostics are used to analyze characteristics of the antiproton beam in the Recycler.

1. Flying wire (FW) is used to measure transverse emittances of the beam. Monitor signals originated from the interaction of the beam particles with carbon filaments are gated to a certain longitudinal region of the beam. The beam profiles from these signals are first fit to a Gaussian distribution (plus a constant) to reduce the effect of noise on the measurements, and the rms width of the fitted curve is used to estimate the emittance. Such measurements were made for both horizontal and vertical planes. However, horizontal and vertical emittances in the Recycler usually are close to one another, and here. we report only the average emittance at different stages of cooling. When the FWs are gated to the core region (see Fig. 1), the data emphasize properties of the beam core; in this case the effect of the tail particles is small. Gating on the tail region gives data describing properties of the newly arrived antiprotons and high momentum particles escaped from the core.

2. Transverse and longitudinal Schottky pickups provide information about transverse emittances and the longitudinal momentum spread, either for the entire beam or for a specific region if gated. The un-gated emittances are measured to accuracy of ~ 10%. The ratio between 95% emittances measured with the Schottky detector and FW varied widely. For a stochastically–cooled beam, when the distribution is close to Gaussian, the ratio was 1.5, and we have not found a good explanation for this difference. The deeper is the effect of electron cooling, the higher the ratio, increasing up to a factor of 3. In the gated mode, an uncertainty in the beam intensity normalization added ~10% error to transverse emittance of the core and even a larger number for the tail.

3. A resistive wall current monitor (RWM) is used to measure the current density distribution along the bunch. An online application program (written by P. Derwent) calculates the portion of the antiproton beam populating the region between barriers #4 and #7, which gives a good representation of the longitudinal tail intensity. Combined analysis of RWM and RF signals allows restoration of the antiproton momentum distribution over the longitudinal action by so-called longitudinal phase-space tomography [7].

4. The main diagnostics for the number of antiprotons in the Recycler, the Direct Current Transformer (DCCT), was not functional in the period when the measurements were made. The available alternatives, a toroid and RWM, are AC coupled and sensitive to the beam temporal structure. As a result, no reliable data for the beam lifetime were available unless the beam loss rate was large .

HEATING PROCEDURES

Successful implementation of the scheme is dependent upon a viable method of additional longitudinal heating of the high transverse amplitude particles in the spatial core to move them into the spatial tail (transition from B to C in Fig. 3). A suitable technique has to provide an optimal balance first, between heating of core particles versus possible degradation of the life time caused by heating of particles in the tail, and second, between applied heating and available strength of electron cooling. Several heating techniques have been tested.

One of the methods was to turn the longitudinal stochastic system into a heating mode by removing the notch filter and gating the system to the core region. The test, however, showed a significant degradation of the beam lifetime.

Another heating technique was shaking the mini-barrier #4. By this method some growth of particle number in the tail region was observed without degradation of the life time. However, it was found to be quite inefficient. Synchrotron frequency of a particle in a barrier RF bucket is proportional to its momentum offset. Consequently, the synchrotron motion of the antiprotons with the momentum close to nominal is slow so that the particles experience infrequent collisions with the moving barrier and are weakly affected by such shaking. At the same time, hot particles can be heated even more that limits the speed and amplitude of shaking. So we abandoned this technique.
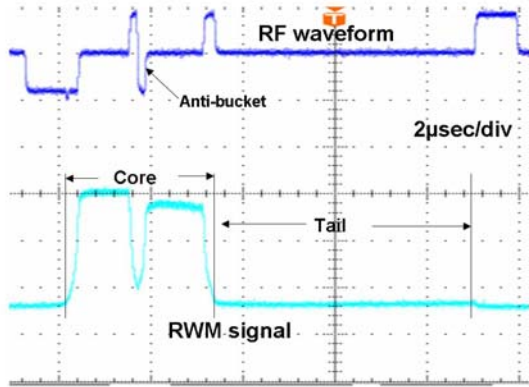

Figure 4. Heating with an anti-bucket. One revolution is shown.

So far, the most promising procedure is beam heating by an anti-bucket [8]. Two narrow barriers with opposite polarities are grown back-to-back in the middle of the core region (Fig. 4), creating a local maximum ("anti-bucket") of the effective potential. The anti-bucket was moved with a random delay in a random direction by 0.6 μs with the speed of 0.8 μs/s. When the anti-bucket is at rest, it provides reflection of antiprotons with 7 MeV/c momentum offset, while the corresponding "height" of the main barriers #6 and #7 is 16 MeV/c. Typically, the time of transition through the anti-bucket is much smaller than the total time of the anti-bucket motion. Hence, the high- offset particles fly through it without changing the

momentum, while the low-offset antiprotons can pick up an additional momentum to be eventually transferred to the tail region.

MEASUREMENTS

Several sets of preliminary measurements, gradually approaching realization of the scheme described above, have been made. First, we cooled the antiprotons in the compound bucket with electron beam only with stochastic cooling turned off. In this case we found that the portion of particles in the tail area decreased rapidly until reaching equilibrium. This clearly indicated a move of antiprotons from area D to A as shown in Fig. 3. The transverse FW emittance of the particles remaining in the tail region decreased at the much slower rate than that of the core. This feature is consistent with the concept of the tail correlation in electron-cooled beam.
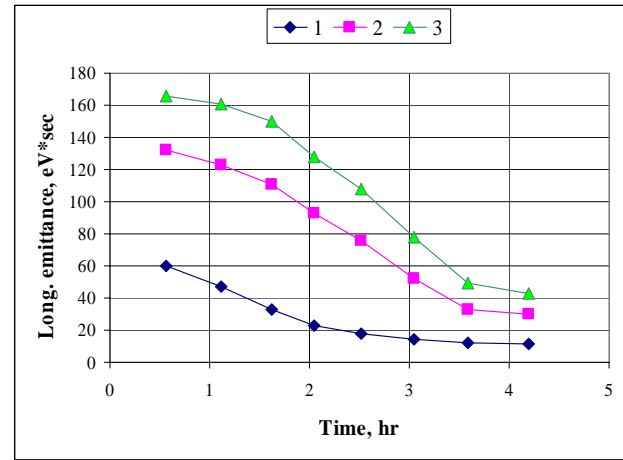

Figure 5. Evolution of the longitudinal emittance in the time of cooling in the compound bucket, restored with longitudinal tomography. The curves 1, 2, and 3 show emittance for 60%, 90%, and 95% of particles, respectively. N_p= 250·10^{10}. A 0.1 A, DC electron beam was on axis for the entire time of the experiment. The gated stochastic cooling was on during hours from 1.5 to 3.5.

In the next measurement, a gated transverse stochastic cooling was applied to the tail region. This resulted in a further decrease of the tail portion of antiprotons as well as in a decrease of the transverse emittance of particles there. In other words, longitudinal cooling rate of electron cooling was significantly enhanced by the gated stochastic cooling (Fig. 5). The portion of tail area particles was decreased to the level of ~5% of the total beam. However, no noticeable change in the Schottky emittance of the core was observed, even though FW showed observable decrease in core emittance. Therefore, we concluded that the naturally occurring longitudinal diffusion for the particles in area B is too weak to overcome the diffusion from A to B.

Further, the injection with momentum coating was adopted. FW emittance of the tail area was larger than that for the core even before applying electron cooling. This is

in agreement with higher emittances of newly injected antiprotons.

Finally, all manipulations were made in accordance with the complete scheme presented in Fig. 3. The total amount of antiprotons in the Recycler used for this experiment was about $230 \cdot 10^{10}$ after beam injections. Out of that, the newly injected beam in three transfers was about $30 \cdot 10^{10}$. Gated stochastic cooling was turned on soon after the injection had been done, and at the same time the electron beam was moved on axis (normally at this number of antiprotons the electron beam is kept at the vertical offset of 2 mm to avoid overcooling and preserve the life time [9]). After half an hour, the anti-barrier was grown, and core region was heated for an hour. At the end of the process, the portion of the hot area particles was found to increase and slowly went up from 5% to ~10%.
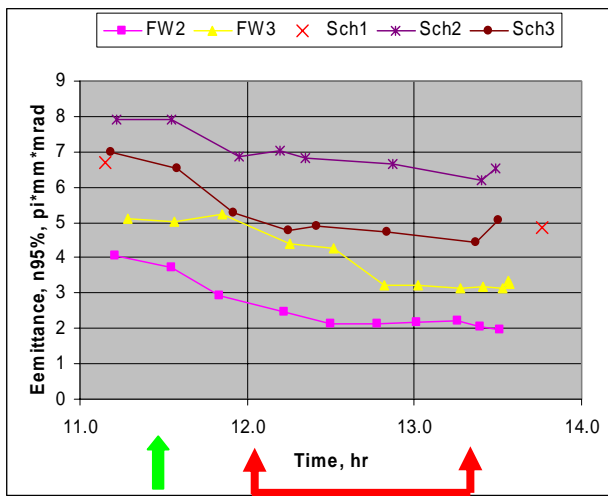

Figure 6. Evolution of emittances during cooling in the compound bucket. FW and Sch indicate average emittance measured with flying wires and Schottky detectors, respectively. Indexes 1, 2, and 3 refer to the entire beam, core region, and tail region, respectively. The single arrow indicates time of turning on the gated stochastic cooling and moving the electron beam on axis. The double-arrow shows time of applying heating by moving anti-bucket.

Evolution of measured FW and Schottky emittances during the final experiment is shown in Fig. 6. For the first time, we observed a significant, ~20%, decrease in the core Schottky emittance as well as all qualitative features of cooling cycle shown in Fig. 3. We hope that eventually it should result in an improvement of the beam lifetime while providing fast cooling. We plan to repeat the measurements with a new DCCT which is being currently installed in the Recycler.

CONCLUSION

Antiproton beam cooling in the compound bucket appears to be a promising way of using both electron and stochastic cooling systems in the Recycler to their maximum strengths. All components of the scheme have been tested successfully. The final judgment about usefulness of the scheme will be made when the measurements are repeated with a good diagnostics for the beam lifetime.

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