STATUS OF THE FERMILAB RECYCLER RING*

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Abstract

The Fermilab Recycler Ring is designed to store antiprotons produced and stacked in the Accumulator, and to recycle antiprotons from the Tevatron left over at the end of a luminosity run. The 8.9 GeV/c fixed energy Recycler is built with an innovative idea of permanent combined function magnets. An antiproton beam lifetime in excess of 100 hours has been achieved. The status of the Recycler commissioning and its planned integration into the Fermilab accelerator complex is presented.

1 INTRODUCTION

The Recycler is a 3319 meter 8.9 GeV/c, permanent magnet storage ring situated within the Main Injector enclosure [1,2,3]. The permanent combined function (or "gradient") magnet technology was chosen based on construction, operational cost and reliability. The first purpose of the Recycler is to ease the requirements for the stacking capability of the existing Antiproton Accumulator. The stacking rate of the Antiproton Accumulator decreases as the stack size increases in the Accumulator. Fig.1 shows the stacking rate as a function of stack size. The Recycler will help keep the stacking rate high by transferring pbars from the Accumulator to the Recycler when the stack size reaches 2~4e11. The Accumulator upgrades are designed to reach a stacking rate of 2e11 antiprotons/hour at a maximum stack size of 5e11 antiprotons.

The second mission of the Recycler is to create the capability to recover unspent antiprotons at the end of the Tevatron Collider stores. Typically >50% of the all the antiprotons initially stored in the Tevatron remains at the end of the store. After a store protons will be scraped away and antiprotons will be decelerated in the Tevatron from 980 GeV/c to 150 GeV/c and transferred to the Main Injector. The Main Injector will decelerate it to 8.9 GeV/c and transfer to the Recycler. This process will increase the available antiprotons for collider operation significantly.

The design goal of the Recycler includes a stacking capability of 2e11 antiprotons /hour up to a total stack size of 3e12 antiprotons. The lifetime of the stored antiproton is expected to be larger than 100 hours with stochastic cooling. An R&D program aimed at developing electron cooling at 8 GeV is currently underway. Electron cooling [4] will be required to support larger stack size.

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Once the Recycler is integrated into the Fermilab Accelerator complex it will be able to support the Fermilab luminosity goal of 2e32 cm-2sec-1.

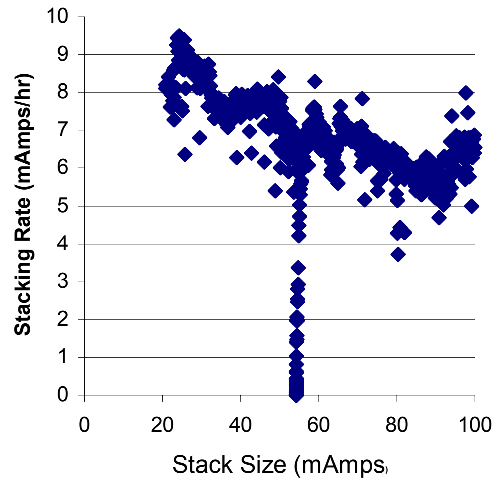

Fig.1 Stacking rate in the Accumulator as a function of stack size.

2 PRESENT STATUS

Recycler Ring commissioning is underway using the proton beam from the Booster. We have also done a limited transfer of antiprotons from the Accumulator to the Recycler and commissioned the Stochastic cooling system.

Fig. 2 shows the injection efficiency of proton beam into the Recycler. The Recycler injection efficiency for protons as produced by the FNAL Booster is better than 90%. The 10% beam is lost rapidly (<50 turns) due to tails in the emittance and limited injection aperture. If we scrape the beam to about 10π mm-mr (95% normalized) emittance (the emittance expected for antiproton after cooling in the Recycler) then 100% of the beam circulated in the Recycler. The circulating beam aperture has been measured to be larger than 30π mm-mr in both planes.

We observe a transverse emittance growth in the Recycler at injection. This growth is partly due to injection lattice mismatch that is caused by ring sextupole field feed down at the injection point, which modifies the beta functions of the off-axis injected beam. The injection mismatch is clearly seen on the IPM injection data Fig. 3. The sigma is oscillating with a frequency twice the betatron frequency of the machine. We are in process of modifying the injection point lattice to fix this problem.

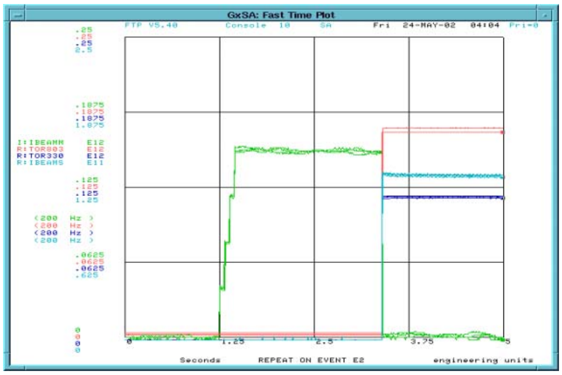

Fig. 2 Injection efficiency into the Recycler. Green trace is beam in Main Injector. Blue is circulating beam in the Recycler.

Magnetic cross talk had initially been a significant effect in the beam lifetime. The Recycler ring is located vertically above the Main Injector in the same tunnel. The Main Injector ramps to 120 or 150 GeV. After significant improvement to the magnetic shielding around the Recycler beam pipe

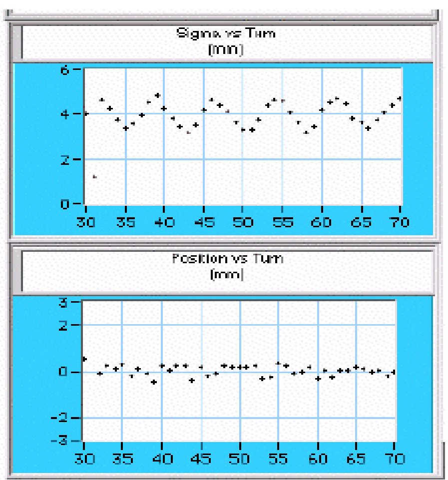

Fig. 3. Sigma vs. turns and position vs. turn for the injected for the injected proton in the Recycler.

and components [5], we have reduced the Recycler orbit motion to about 0.7 mm (rms) and 0.35 mm (rms) in horizontal and vertical planes respectively. Orbit motion at this level does not have a significant effect on the Recycler Stochastic cooling performance or beam lifetime. The tune of the Recycler also moves by 0.01 due to the Main Injector ramp. Both the orbit and tune motion will be further reduced by active ramped dipole and quadrupole elements.

The Recycler performance at present is also limited by a sizable emittance growth observed in transverse planes for a stored beam. Although this emittance growth can be overpowered by the stochastic cooling at small stack size, the equilibrium emittance suffers. This remains a concern for attaining high luminosities using the Recycler without electron cooling. The growth has been measured to be about 5π mm-mr in both planes have been observed for both stored proton and antiproton beams. The beam lifetime of the proton beam is about 70 hours with out cooling. A detailed model of the Recycler Ring vacuum has been made to understand the emittance growth. The gas composition in the beam pipe has been measured by using RGA. Emittance growth and lifetime calculated based on this model is consistent with the beam measurements with in a factor of two. At present we believe that the Recycler lifetime and emittance growth to be vacuum dominated, although substantial sensitivity to the machine operating point is also present.

The Recycler Ring has 4 stochastic cooling systems. The transverse planes are cooled by 2-4 GHz bandwidth betatron-cooling systems, and a pair of 1-2 GHz and 0.5-1 GHz cooling systems is used for momentum cooling. The commissioning of these cooling systems has started by storing antiprotons into the Recycler.

The antiprotons are transferred from the Accumulator to the Main Injector in 53 MHz rf buckets. In the Main Injector they are coalesced into 2.5 MHz and decelerated by about 40 MeV/c to match the Recycler central momentum. The pbar are then transferred into the Recycler, with the previously transferred antiprotons segregated to a different part of the circumference using an RF "Barrier Bucket". The injected beam is de-bunched into the rf barrier bucket and further rf manipulations merges the two rf barrier buckets of stored and injected beam. Stochastic cooling only works on the beam stored in the barrier bucket. Fig. 4 shows the stacking of antiproton in the Recycler. At present due to the aperture limitations and limited tune-up of the antiproton injection line, we have achieved a best transfer efficiency of about 50%; with an over all transfer efficiency of only about 30%-40%.

Fig. 5 shows the effect of transverse Stochastic cooling on the transverse emittance of the antiproton beam. The initial growth is due to vacuum and injection related effects, which are under study. When the cooling is turned on the beam cools down to equilibrium emittance in less than 30 minutes. An antiproton lifetime of greater than 100 hours has been achieved for a stack size of 2e11 antiprotons. The design goal is to reach similar lifetime with 3e12 antiprotons. Further tuning of the cooling system and injection process is in progress with the goal of demonstrating higher stack sizes in the Recycler.

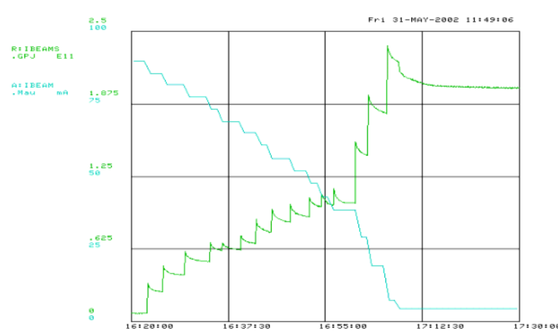

Fig. 4. The antiproton un-stacking and stacking between Accumulator and Recycler. Blue line is Accumulator

antiproton beam intensity in mAmp (1mAmp=1e10 antiprotons). Green is Recycler intensity in 1e11.

3 RECYCLER UPGRADE

The Recycler Ring's performance is at present limited by 1) Injection mismatch 2) Tight injection line aperture 3) Emittance growth rate due to vacuum 4) Effect of Main Injector ramp on the Recycler orbit and tune and 5) lack of complete instrumentations.

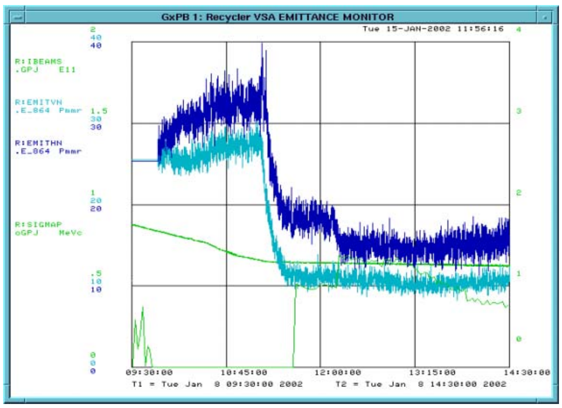

Fig. 5. Transverse emittance of pbar when the cooling system is switched on. Also shown in beam intensity in Green.

We are in process of upgrading the Recycler to address these issues. We will have two shutdowns this year to install upgrades in the Recycler. Correction magnets will be added at the injection points to address the injection mismatch problem. We are carrying out a detailed measurement of the Recycler injection aperture. An independent study is underway to investigate replacement of the existing injection and extraction beam lines with larger aperture and simpler beam lines.

The Recycler vacuum will be upgraded by installing additional ion pumps at unused pump-out ports in the Recycler. This will double the number of ion pumps. The new ion pumps also have the capability to remove inert gases. It is expected that the pressure of Ar will go down by roughly a factor of 2-3. We have introduced a new bake out system for the Recycler. The original system had to be removed when it was discovered that the heater tapes used was weakly magnetic and destroyed the magnetic field quality. We plan to bake the whole Recycler to >110 deg C for four days to remove water. The vacuum will also be monitored by more ion gauzes and residual gas monitors. A calculation shows that the improvements to the Recycler vacuum should give us up to a factor of three increases in lifetime.

We have installed dipole correctors in every half-cells of the Recycler. Ramp capable control cards on these corrector power supplies will allow us to ramp the dipole and quadrupole trim magnets to control the orbit and tune motion of the Recycler. We are also improving the passive shielding around the Recycler.

An R&D is underway to upgrade the Recycler BPM system and add additional detector to monitor the beam. The BPM system is extremely challenging due to the variety of RF structure, bunched and unbunched beams, etc. in the Recycler. After the Fall 2002 shutdown we plan to start integrating the Recycler into the Fermilab Accelerator Complex.

4 ACKNOWLEDGEMENTS

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