# DIRECT ANTIPROTON DECELERATION IN THE FERMILAB PROTON DRIVER

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*Abstract*

The Fermilab Proton Driver is an 8 GeV kinetic energy H- linear accelerator proposed as a new source of high brightness protons for the Main Injector. The Recycler ring is an 8 GeV antiproton storage ring that resides in the same tunnel as the Main Injector. This paper describes a scenario wherein the current Main Injector proton injection kickers and Lambertson magnet are moved vertically into the Recycler ring to enable antiproton extraction toward the Proton Driver. By employing a pair of intermediate vertical bends at the appropriate vertical betatron phase advance, the vertical dispersion into the Proton Driver can be eliminated and direct antiproton deceleration made possible. Because the H- and antiproton beams have the same charge but opposite direction, matching of the Recycler lattice to the Proton Driver is required to accommodate the reversed effect of the focusing and defocusing quadrupoles.

## ANTIPROTON EXTRACTION

The Fermi National Accelerator Laboratory (Fermilab) [1] Proton Driver is discussed in a number of other papers at this conference. The key pieces of information relevant to this paper are the facts that the elevation of the Proton Driver is the same as the Main Injector [2], and the injection point is at the MI-10 location. Another relevant piece of information is that the Recycler Ring [3] resides directly above the Main Injector, and has Twiss parameters that are similar to that of the Main Injector.

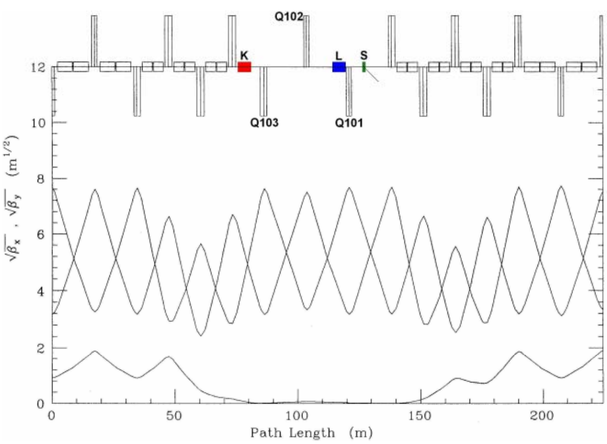


Figure 1: Lattice functions of the Recycler Ring, indicating the approximate positions of the kicker (K) and Lambertson (L) magnets at the MI-10 location.

When the Proton Driver is installed and becomes operational, the existing kicker and Lambertson magnets will be removed from the Main Injector. It is proposed in this paper to raise those beamline elements upward and install them into the Recycler ring. Figure 1 shows the lattice functions of the Main Injector, which are very similar to those of the Recycler Ring. The placement of the kicker and Lambertson magnets are also indicated.

Following the Lambertson, propagating in the direction toward the Proton Driver, four vertical bending magnets are employed to lower the elevation of the antiprotons to that of the Proton Driver. The magnets are spaced at the appropriate locations required to suppress vertical dispersion once the Proton Driver elevation is achieved.

## PHASE SPACE DENSITY

Because the Recycler Ring presently depends on the use of stochastic cooling [3] to increase and maintain the longitudinal density of the antiprotons, there is a dependence of this density on the number of particles in the antiproton stack. This dependence is shown in figure 2.

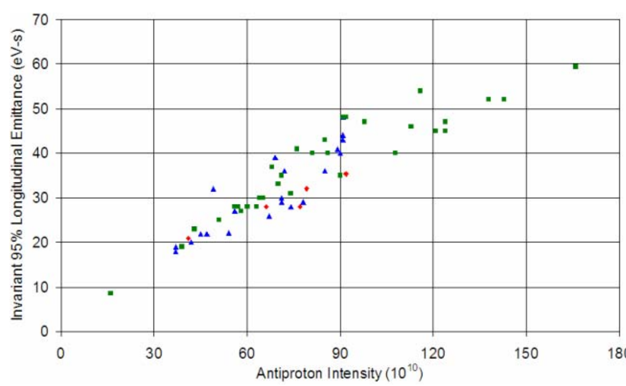


Figure 2: Measured dependence of Recycler invariant 95% longitudinal emittance as a function of antiproton intensity.

Note in figure 2 that the longitudinal density of the antiprotons, under tuned up conditions, is invariant. As will be seen in subsequent sections, the desired invariant 95% longitudinal emittance per bunch is 0.00025 eV-sec. According to the data in figure 2, this corresponds to a bunch intensity of 6.4x$10^6$, or an instantaneous beam current of 0.33 mA.

## ANTIPROTON BUNCHING

Because it is desired to decelerate antiprotons all the way up the Proton Driver through the RFQ [1], a bunch frequency of 325 MHz is required. This frequency is not compatible with the central orbit of the Recycler Ring, which is a permanent magnet synchrotron. The closest harmonic of the Recycler Ring is 3619, which corresponds to a fractional momentum offset of -1.14%.

Because the peak dispersion function in the Recycler Ring has an amplitude below 2 m, this represents a closed orbit with a peak displacement toward the inside of the



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ring of less than one inch. This is well inside the physical aperture of the ring, but may require considerable tuning to assure long term lifetime at this orbit.

Table 1: Recycler 325 MHz bunching parameter values.

| Parameter | Value |
|---|---|
| Beam Momentum (MeV/c) | 8787.41 |
| Kinetic Energy (MeV) | 7899.088 |
| Relativistic Energy | 9.418758 |
| Relativistic Velocity | 0.994348 |
| RF Voltage (kV/turn) | 8 |
| RF Harmonic Number | 3619 |
| Momentum Compaction Factor | -0.009168 |
| Revolution Frequency (kHz) | 89.803 |
| Synchrotron Frequency (kHz) | 0.197 |
| RF Bucket Half Height (MeV) | 1.165 |
| RF Bucket Area (eV-sec) | 0.00456 |
| Invariant 95% Bunch Area (eV-sec) | 0.00025 |
| RMS Bunch Length (ns) | 0.1053 |
| RMS Energy Spread (MeV) | 0.126 |

The first step of antiproton extraction from the Recycler Ring is to use the existing barrier bucket RF system to extract $8.3 \times 10^8$ antiprotons from the stack and shape them into a 1.6 µsec long band of charge. This is the length of the kickers that will be used for extraction.

The next step is to segregate this charge into 129 bunches using a 325 MHz RF cavity installed into the Recycler Ring. Table 1 contains a list of ring and RF parameters. With the goal of reducing the bunch lengths to less than a wavelength at 1300 MHz, a 325 MHz peak voltage of 8 kV/turn is required. Figure 3 shows the results of a multiparticle simulation showing the resultant phase space distribution.

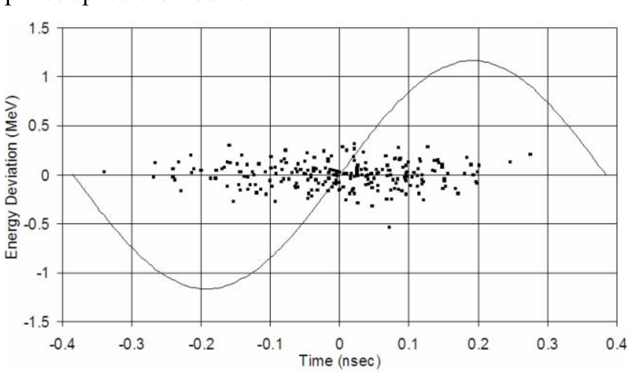


Figure 3: Simulation of the initial bunching performed by the 325 MHz RF cavity inserted into the Recycler Ring. A 1300 MHz RF waveform of arbitrary amplitude is superimposed to show the capture requirements for the next stage of bunching.

A design goal for this paper is to generate an antiproton phase space density distribution at the 8 GeV end of the Proton Driver that is identical to the H-minus distribution assuming SNS emittances [4]. This requires that the bunches be further reduced in length by a factor of 20x. If only 325 MHz cavities were in the ring, a peak voltage of 4 MV/turn would be required.

In this paper it is assume that a high power 1300 MHz system is utilized with a peak voltage of 1 MV/turn. The parameters of this RF system are shown in table 2. Because the synchrotron tune is so large at this voltage, the separatrix of the associated RF bucket is deformed. Figure 4 shows an antiproton bunch and separatrix.

Table 2: Recycler 325 MHz bunching parameter values.

| Parameter | Value |
|---|---|
| Beam Momentum (MeV/c) | 8787.41 |
| Kinetic Energy (MeV) | 7899.088 |
| Relativistic Energy | 9.418758 |
| Relativistic Velocity | 0.994348 |
| RF Voltage (kV/turn) | 1000 |
| RF Harmonic Number | 14476 |
| Momentum Compaction Factor | -0.009168 |
| Revolution Frequency (kHz) | 89.803 |
| Synchrotron Frequency (kHz) | 4.415 |
| RF Bucket Half Height (MeV) | 6.511 |
| RF Bucket Area (eV-sec) | 0.00638 |
| Invariant 95% Bunch Area (eV-sec) | 0.00025 |
| RMS Bunch Length (ns) | 0.0223 |
| RMS Energy Spread (MeV) | 0.5955 |

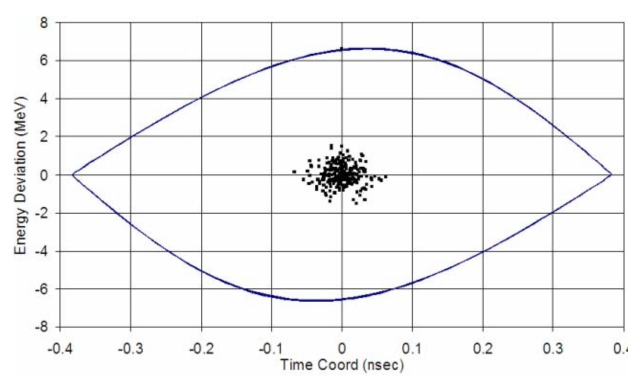


Figure 4: Simulation of the bunch compression accomplished after turning on the 1300 MHz RF cavity inserted into the Recycler Ring. The distortion of the RF bucket due to large synchrotron tune is apparent.

Now, it turns out that this bunch length is still too long. Further increases in voltage are ruled out for a single cavity location due to the increasing large phase space distortion. Therefore, either more cavities must be installed around the ring at roughly equal intervals around the circumference, or a simple bunch rotation can be employed. The latter is the preferred solution, which only requires the RF voltage to be reduced by a factor of 2x for a duration of nine turns. Five turns later the antiproton distribution is shortened to an rms bunch length of 0.0157 nsec.

## DEBUNCHER CAVITY

At this point the train of 129 antiproton bunches are extracted from the Recycler using the kicker and Lambertson magnets. After traversing the Recycler transfer line down to the nominal Proton Driver transfer line, the antiprotons reach the debuncher cavity. Figure 5 shows the bunch rotated antiproton charge distribution, superimposed on the 1300 MHz debuncher waveform of arbitrary amplitude.

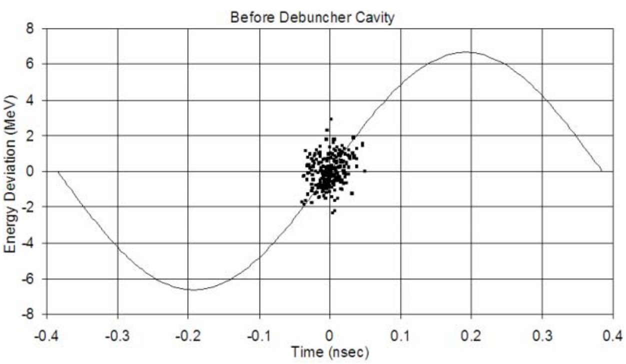


Figure 5: Simulation of a bunch after bunch rotation in the Recycler Ring and transport up to but before the debuncher cavity. The debuncher waveform is superimposed with an arbitrary amplitude.

The purpose of the debuncher cavity is to reduce the energy spread of the H-minus bunches coming out of the Proton Driver. In this paper the opposite effect is desired. The small energy spread antiprotons are correlated in phase space so that when they reach the 8 GeV end of the Proton Driver they have the same uncorrelated phase space shape as the H-minus bunches. Figure 6 shows the effect of the 50 MV debuncher waveform on the antiproton distribution.

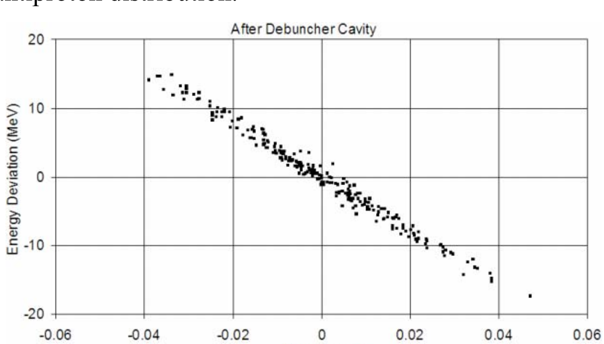


Figure 6: Simulation of the phase space correlation imposed on each bunch by the debuncher cavity operating at the nominal peak voltage gain of 50 MV.

The distance from the debuncher cavity to the Proton Driver is 582 m. Figure 7 shows the phase space distribution of an antiproton bunch at the 8 GeV end of the Proton Driver. Note that there are no residual correlations in phase space. The rms bunch length and energy spread are very similar to the H-minus bunches generated by the Proton Driver assuming SNS emittances.

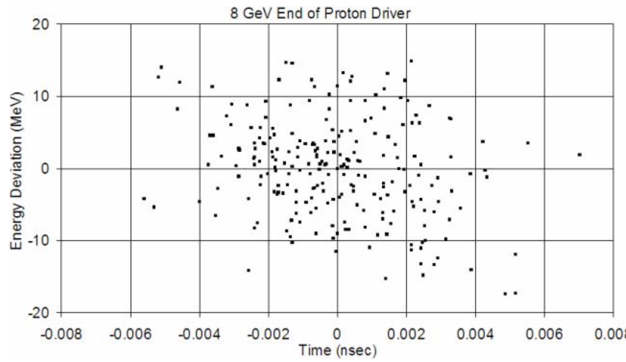


Figure 7: Simulation of a bunch at the 8 GeV end of the Proton Driver. This phase space distribution is identical to the H-minus output of the Proton Driver assuming SNS emittances.

## FUTURE WORK

The next step is to propagate the antiprotons up the Proton Driver lattice. Because the beam current is so low, space charge will play a negligible role. In addition, deceleration leads to gap focusing rather than defocusing, which should yield tighter focusing functions that will offset the larger invariant 95% transverse emittances of 5 πmmmr that are observed in the Recycler Ring.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] G.W. Foster, “An 8 GeV Superconducting Linac”. this conference; Internal Fermilab Memo FNAL-TM-2169 (Part II).,

[2] Fermilab Main Injector Technical Design Handbook; S.Mishra, “High Luminosity Operation of the Fermilab Accelerator Complex”, Proc. U.S. Part. Accel. Conf. (2003).

[3] G.P. Jackson, ed., "Fermilab Recycler Ring Technical Design Report”, TM-1991 (1996); G.P. Jackson and G.W. Foster, "Storage Ring for Enhanced Antiproton Production at Fermilab", Proc. U.S. Part. Acc. Conf., Dallas (1995); G. Jackson, "Operational Experience with the Permanent Magnet Recycler Ring at Fermilab", European Part. Acc. Conf., Vienna (2000).

[4] “Preliminary Design Report - Superconducting Radio Frequency Linac for the Spallation Neutron Source”, SNS-SRF-99-101 (December 20, 1999).

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