RF Exercises Associated with Acceleration of
Intense Antiproton Bunches at Fermilab

J.E. Griffin, J.A. MacLachlan, Z.B. Qian,*

Fermilab,* P.O. Box 500, Batavia, Illinois 60510

Summary

Antiprotons for the Fermilab $\bar{p}p$ colliding beam project (Tevatron I)¹ will be extracted from an 8 GeV accumulation ring in a few (1 to 3) bunches of $\sim 10^{11}$, a single bunch at a time. To preserve the stack as a source of subsequent bunches, each bunch will be removed from the dense core of the stack with an isolated bucket² at harmonic number $h = 2$. The longitudinal emittance of the bunches will be in range 1.5 to 2. eVs, roughly five times what the Main Ring usually accelerates with the installed 53 MHz rf system. Therefore, the bunch is to be narrowed on the Accumulator extraction orbit to match a 2.5 MHz bucket in the Main Ring. By raising the 2.5 MHz voltage (harmonic number $h = 53$), the bunch will be further narrowed in the Main Ring to span seven buckets of the principal system ($h = 1113$). The bunch will then be captured adiabatically from the $h = 53$ bucket into seven adjacent $h = 1113$ buckets for acceleration to a 150 GeV flattop. At this energy the 2.5 MHz and 53 MHz systems will be used jointly to coalesce³ the seven bunches into a single $h = 1113$ bucket for injection into the Energy Doubler. This paper describes unstacking in the Accumulator, the adiabatic capture into seven bunches in the Main Ring, and the coalescing of the seven back into one bunch at 150 GeV. The expected performance of the whole sequence has been established by detailed particle tracking simulation, and tests of some phases have been made in the Main Ring.^{4,5}

Unstacking With an Isolated Bucket

The Accumulator⁶ will be an 8 GeV storage ring using stochastic cooling to collect $\sim 4.5 \times 10^{11}$ antiprotons over a four hour interval into a stack consisting of a dense core and a diffuse tail. The core will have an essentially Gaussian energy distribution with rms width $\sigma_E = 2$ MeV and peak density 10^5 /eV. The most relevant parameters of the accumulator are collected in Table I. Bunches of $\sim 10^{11}$ antiprotons are removed sequentially by acceleration in a harmonic number $h = 2$ isolated bucket, i.e., a bucket provided by a broadband rf system that acts on only one half of the azimuthal distribution of antiprotons. This system was selected in preference to a conventional $h = 1$ system because it leads to a more practical voltage requirement. The voltage required for a given bucket area, i.e., to encompass a desired number of antiprotons, is proportional to h^3 . For a stationary bucket with $h = 1$ the voltage is ~ 2.4 volts for our application, so low that precise control is problematic and acceleration is unacceptably slow. The choice $h = 2$ requires a few tens of volts from the broadband cavity and permits unstacking in about 10 s. We consider two modes of unstacking viz., establishing a moving bucket of the correct area suddenly in the middle of the stack or, alternatively, adiabatic capture and gradual initiation of acceleration.

To be specific we illustrate the unstacking of 8×10^{10} antiprotons from the core. They span ± 452 keV around the mean of the energy distribution. The particle revolution period is $\tau = 1.59 \mu s$; thus the emittance of the desired particles is 1.44 eVs. For the adiabatic capture technique 1.44 eVs is also the required bucket area. The calculation of the area for a moving bucket to encompass the same number of antiprotons is tedious; for an arbitrary choice of stable phase $\phi_s = 20^\circ$ the required bucket area is 1.8 eVs. Fig. 1 shows a bunch which is being unstacked from the core distribution with the sequence of adiabatic capture (duration 1.59s, $V_{final} = 14.24V$) and adiabatically established acceleration (duration 22.3s, $\phi_s = 20^\circ$, $V_{final} = 59V$) at the time (22.9s, $V = 59V$) when the bunch has fully cleared the core. The energy distribution of the core and the isolated bunch are histogrammed in Figure 2. Also shown in Fig. 2 is the corresponding histogram for a moving bucket capture (duration 11s, $\phi_s = 20^\circ$, $V = 72V$) at 1.1 sec. These distributions show that not only is the first bunch extracted by moving bucket capture less dense but furthermore the remaining stack core is more disrupted. Thus, for subsequent bunches the comparison of the two methods will be even less favorable for moving bucket capture.

Capture and Acceleration to 150 GeV

The bunch extracted from the Accumulator is synchronously injected into a stationary 2.5 MHz ($h = 53$) bucket in the Main Ring. The Main Ring parameters most directly related to the rf systems are collected in Table II. The voltage is then raised from 3.3 kV to 16.8 kV thereby shortening the bunch from about 200 ns to 132 ns, equal to seven periods for the principal 53 MHz ($h = 1113$) system. The antiprotons are next captured into seven adjacent $h = 1113$ buckets by raising the 53 MHz voltage from minimum (~ 10 kV) to 1 MV over 70 ms. It is possible to obtain a minimum voltage ~ 10 kV from the principal rf system by counterphasing the drive to the cavities in two equal groups. To determine the dilution caused by this subdivision and later recombination at 150 GeV one must find the distribution of antiprotons between and within the $h = 1113$ bunches. Fig. 3 shows the distribution obtained in this sequence of operations. The central bunch has an emittance of .32 eVs; the total emittance has grown by 7%.

Only the central bunch has been tracked in detail through the Main Ring acceleration cycle to 150 GeV using magnetic field ramp parameters etc. typical of present practice. In this tracking a dilution of 30% was found, a result which is consistent with longitudinal emittance measurements made at several times in the Main Ring cycle.⁵ The other bunches were diluted by the same factor to provide a distribution for testing the coalescing process. This expedient leads to a slight overstatement of the dilution because we have found both by observation and simulation that smaller bunches suffer less than larger ones in crossing transition. We expect to reduce the dilution somewhat by improvements in the magnetic field ramp and low level rf system.⁷

*Visiting scientist, University of Peiking

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Bunch Coalescing at 150 GeV

The basic scheme for recombining the antiprotons into a single 53 MHz bunch consists of three steps: 1) reducing the $h = 1113$ voltage slowly in the presence of a fixed $h = 53$ voltage which will capture the particles as they are lost from the shrinking buckets, 2) rotating the coalesced ensemble to a narrow phase spread by raising the $h = 53$ voltage suddenly to create a mismatched bucket, and 3) suddenly turning on the $h = 1113$ voltage to provide a bucket matching the ensemble at the instant of minimum phase width. The proper $h = 53$ voltage is established by requiring that as particles start to escape the central bunch they lie on a trajectory which just encloses the outermost bunches. The word "slowly" in step 1 means specifically about $1/4$ of an oscillation period in the low frequency bucket so that the particles have time to fill in smoothly along the $h = 53$ trajectories. Then as the $h = 1113$ voltage is reduced to a low level the particles uniformly fill a contour extending over $\pm\pi/3$ radians in the unperturbed $h = 53$ bucket. The very low 53 MHz voltage required in this operation will be provided by a low shunt impedance auxiliary cavity capable of a maximum of ~ 10 kV. At this point the low frequency voltage is raised suddenly to make the now mismatched bunch rotate in the bucket. After $\sim 90^\circ$ of rotation the bunch has its minimum width; for sufficiently high voltage the bunch will be narrow enough to fit in an $h = 1113$ bucket. The amount of $h = 53$ voltage required for the bunch rotation can be reduced by first adiabatically debunching the coalesced ensemble from $\pm\pi/3$ to, say, $\pm\pi/2$. However, debunching in the low frequency bucket is time consuming, and one may prefer to provide twice the voltage instead.

The 1.5 eV bunch delivered from the accumulator has been diluted to about 2.3 eV by the time it reaches 150 GeV as seven bunches, most of the dilution occurring in various steps of the conventional acceleration cycle. The central bunch has an emittance of .42 eV which fills 10% of the 1 MV stationary $h = 1113$ bucket. Therefore, when the voltage has been dropped by a factor of 100 the antiprotons begin to escape the central bucket and flow along closed contours in the low frequency bucket. Fig. 4 shows this process half way through when the 53 MHz voltage has been reduced to 2.4 kV. The two bunches flanking the central bunch have been omitted to clarify the phase motion. The solid lines indicate the boundary of the ultimate $h = 53$ bucket. The correct 2.5 MHz voltage is obtained from the simple consideration that the debunched ensemble is to lie within a matched contour extending over $\pm\pi/3$ radians of rf phase in a stationary bucket. Therefore, the bucket height should be just twice the bunch height. Assuming that one completely removes all of the $h = 1113$ structure without dilution, the bunch height should be simply $2.3 \text{ eV}/(7 \times T_{\text{rf}}) = 17.4 \text{ MeV}$ and the $h = 53$ bucket height should be 35 MeV. In Fig. 4 the bucket height is somewhat less (24.5 MeV) so that the bunch height is not perfectly matched. However, the voltage is raised for the bunch rotation before there has been any significant spreading of the bunch. Figure 5 shows the result of quickly raising the $h = 53$ voltage to 62 kV and waiting for 4 ms, just over $1/4$ synchrotron oscillation period. The dashed curves show the boundary of the 62 kV, $h = 53$ bucket. The solid curve is the 2.4 eV $h = 1113$ bucket which is turned on suddenly to capture the bunch for synchronous injection into the Energy Doubler. This bucket requires 350 kV from the 53 MHz system. The figure shows $< 5\%$ loss, which one could eliminate by

realistic parameter changes at any of several different places in the overall scheme. The parameters used here are precisely those of the Tevatron I Design Report.⁸ Because we have good prospects for reducing the dilution during acceleration we expect the design values to be completely adequate, but in any case we expect new values to be established as the operation of the new facility is optimized. The flexibility for such optimization has been incorporated in the design.

Conclusion

Fermilab's $\bar{p}p$ colliding beam project requires specialized rf procedures for unstacking single bunches of $\sim 10^{11}$ antiprotons from the core of the 8 GeV stack in the Accumulator and accelerating them in the Main Ring with minimum dilution of longitudinal phase space. These bunches have ~ 5 times the longitudinal emittance ordinarily accelerated in the Main Ring. Therefore techniques have been developed to partition each bunch into seven adjacent bunches immediately upon injection into the Main Ring and to subsequently recombine them into a single bunch for injection into the Energy Doubler. These manipulations involve somewhat intricate programming of the principal 53 MHz rf system and an auxiliary 2.5 MHz system, but both particle tracking simulation and preliminary experiments in the Main Ring show that they can be performed without significant dilution of the antiproton phase space density.

References

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Table I - Accumulator Parameters

Antiproton beam kinetic energy	8.0	GeV
Number of antiprotons in stack core	4.5×10^{11}	
RMS width of core energy distribution	2.	MeV
Peak density of core energy distribution	1×10^5	(eV) ⁻¹
Mean radius	75.47	m
Revolution period	1.59	us
RF frequency (h=2, isolated bucket)	1.264	MHz
Transition gamma (γ_t)	5.65	
Maximum rf voltage (h=2, isolated bucket)	100.	V
Maximum rf voltage (h=2, resonant)	1.	kV

Table II - Main Ring Parameters for p Acceleration

Antiproton beam kinetic energy at injection	8.0	GeV
Number of bunches (h=53)	1	
Number of bunches (h=1113)	7	
Number of antiprotons	$\sim 10^{11}$	
Longitudinal emittance (95%)	1.5	eVs
Mean radius	1.0	km
RF frequency at injection (h=53)	2.515	MHz
RF frequency at injection (h=1113)	52.813	MHz
Transition gamma (γ_t)	18.75	MHz
Maximum rf voltage (h=53)	62.	kV
Maximum rf voltage (h=1113)	4.	MV
Maximum rf voltage (h=1113, aux. cavity)	1.	kV

Fig. 1: Unstacking in Accumulator

Fig. 2: Energy distribution in unstacking

Fig. 3: Capture in Main Ring (2.5 MHz to 53 MHz)

Fig 4: Bunch coalescing in Main Ring

Fig. 5: Recapture at 53 MHz in Main Ring