BEAM MANIPULATION AND COMPRESSION USING BROADBAND RF SYSTEMS IN THE FERMILAB MAIN INJECTOR AND RECYCLER

G. William Foster, C. M. Bhat, B. Chase, K. Seiya, J. A. MacLachlan,
P. Varghese, D. Wildman
FNAL, Batavia, IL 60510, USA

Abstract

A novel method for beam manipulation, compression, and stacking using a broad band RF system in circular accelerators is described. The method uses a series of linear voltage ramps in combination with moving barrier pulses to azimuthally compress, expand, or cog the beam. Beam manipulations can be accomplished rapidly and, in principle, without emittance growth. The general principle of the method is discussed using beam dynamics simulations. Beam experiments in the Fermilab Recycler Ring convincingly validate the concept. Preliminary experiments in the Fermilab Main Injector to investigate its potential for merging two "booster batches" to produce high intensity proton beams for neutrino and antiproton production are described.

INTRODUCTION

Intense proton beams are needed to produce high intensity neutrino beams at various high energy accelerator facilities around the world. At Fermilab, intense proton beams on the antiproton target are desired to produce high intensity antiprotons for collider operation. This has prompted the development of alternative methods of providing higher intensity protons on target by merging beams from two "Booster Batches" into a single pulse. These include "slip stacking" [1] and the use of a barrier bucket systems [2]. Both of these schemes result in significant longitudinal emittance growth, both in theory and in practice. This emittance growth is detrimental for antiproton production where the smallest possible bunch length on target is desirable and for neutrino production where the longitudinal emittance growth can result in beam losses which limit operational intensities.

In this paper we report on a new method to produce intense protons by fast compression of more than two batches using a broadband "arbitrary waveform" RF system. Though the method is very general, we describe the technique in reference to an application to the Fermilab Main Injector [3] and Recycler [4].

At Fermilab, the proton beam from the 8 GeV Booster arrives at the Main Injector in a batch of 84 buckets of 53 MHz. The total length of the batch is about 1.59 μsec. One can transfer up to six similar batches of protons to fill the Main Injector. In the scheme described here one can inject up to six batches of Booster beam, debunch adiabatically to form a long bunch, compress them appropriately, re-bunch in 53MHz, inject more Booster beam and accelerate them to 120 GeV/150 GeV. Thus one

can increase the beam intensity per Main Injector acceleration cycle.

PHYSICS OF FAST COMPRESSION AND EXPANSION

Concept

A debunched beam can be confined to a fraction of the azimuth of a synchrotron ring by a set of "Barrier Pulses" [2] that repel particles trying to escape from the ends of the segment of beam. In such a system, the azimuthal extent of the beam can be compressed (or expanded) by slowly moving the barrier buckets together (or apart)[4]. If the barrier pulses are moved slowly enough the longitudinal emittance is preserved.

The principle of beam compression described here is to produce a velocity tilt by using a series of voltage ramps in the region between the pulses that contain the beam. In the presence of the velocity tilt, the beam shears in such a way that the bunch is compressed– essentially a rotation of a long bunch in $(\Delta E, \theta)$ phase space, where ΔE is the energy offset and θ is the co-moving azimuthal coordinate. The voltage ramp is reversed when the momentum spread of the beam is very close the height of the barrier bucket confining the beam or close to the momentum acceptance of the synchrotron. In presence of voltage ramp of opposite slope the particles will come relatively to rest and reverse their direction of synchrotron motion resulting in further compression of the bunch. During compression, the barrier pulses are moved so that they follow the particles at the ends of the batch, keeping particles from leaking out the ends.
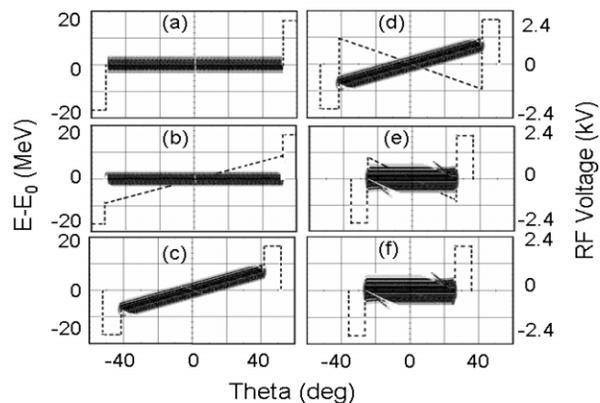

Figure 1: RF waveforms and phase space distribution for beam compression. The sequence is reversed for beam expansion.

The method described here is comparable to the drift compression schemes proposed for Heavy Ion Fusion [5] in which a velocity tilt plus "ear pulses" to contain the ends of the beam are planned to compress the beam on target. The difference here is that we remove the velocity tilt at the end of the compression, whereas in the case of Heavy-Ion Fusion the large momentum spread is maintained all the way to the target.

Beam Dynamics Simulations

The mechanics of RF gymnastics for beam compression in the Main Injector and Recycler were demonstrated by simulations using ESME [6]. Figure 1 shows ($\Delta E,\theta$) – phase space beam particle distribution for various stages of beam compression of two batches of proton in the Main Injector at 8 GeV. Each batch of longitudinal emittance of 8.5 eVs is injected contiguously into a rectangular barrier bucket (dashed line) as shown in Figure 1(a). The amplitude of barrier pulse used to confine beam is 2 kV. Both of these synchrotrons operate below "transition energy" at injection energy. Therefore, to perform a bunch rotation, the region between barrier pulses is replaced by a linear ramp as shown in Figure 1(b). In 96 msec the batches get oriented as shown in Figure 1(c). During this time, the barrier pulses are also brought closer to stop leakage of the beam particles at the both ends. Before the energy spread of the beam exceeds that of the barrier bucket, the linear ramp with positive slope is replaced by that with negative slope for an equal number of revolution periods (see Figure 1(d)). Now, the particles change their direction of motion in ($\Delta E,\theta$) – phase space as compared with that in Figure 1(b) and 1(c). As a result of this the beam gets compressed. As soon as a stage 1(e) is reached the linear voltage ramp between barrier pulses is turned off as shown in Figure 1(f).

The compression speed is limited by the ramp voltage (which determines how fast the velocity tilt can be applied to the beam) and by the momentum aperture of the ring (which limits the maximum velocity shear between the beginning and end of the beam). The total time required for bunch compression in this example was about 190 msec.

The emittance growth for this process is ideally zero in the limit of a beam perfectly matched to infinitely high barrier pulses. This beam simulation with realistic voltage and beam matching conditions shows no beam loss and <10% emittance growth.

BEAM EXPERIMENTS

Demonstrations for proving the principle of beam compression and expansion were carried out first at the Fermilab Recycler and later in the Main Injector. In both cases we used one batch of Booster proton beam and compressed to half of its original size essentially following the steps outlined in the simulation.

Experiments at the Fermilab Recycler

The Fermilab Recycler is an 8 GeV storage ring built to be as the main anti-proton storage ring for the Fermilab collider program. All RF manipulations in the Recycler were carried out using a barrier RF system [7]. The Recycler low-level RF system was programmed to regenerate an arbitrary waveform with the required characteristics with an update rate of 720 times a second.
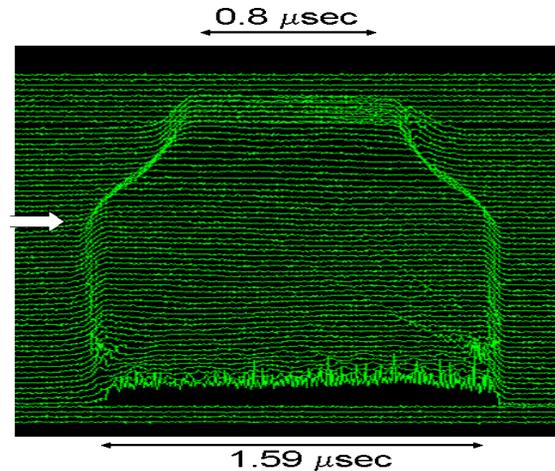

Figure 2: Wall current monitor (WCM) data taken during bunch compression in the Recycler. The time goes from bottom to top from beam injection to extraction. The data is taken at 10 msec/trace and compression takes about 200 msec using a +/-1 kV ramp voltage.
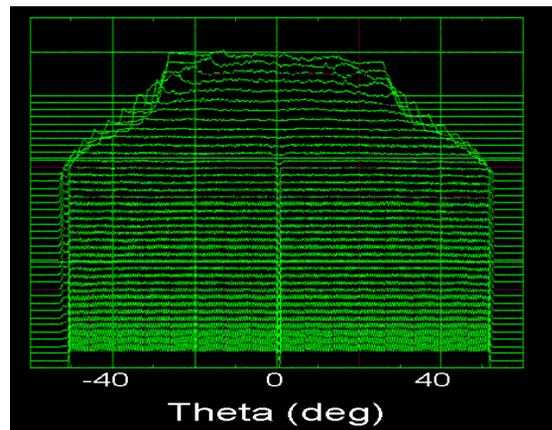

Figure 3: Simulated WCM data using ESME. All observed features in the experimental data are qualitatively seen here.

A batch of Booster proton beam was first injected into the Main Injector and transferred to the Recycler into a barrier bucket made up two rectangular barrier pulses of 2 kV each. The pulse gap was matched to that of the injected beam and the pulse width was 0.9 μsec. The beam energy spread was estimated to be about 5.7 MeV.

Figure 2 shows the wall current monitor (WCM) data taken during bunch compression from 1.59 μsec to 0.80 μsec in the Recycler. The total time required for compression was about 200 msec. The beam was extracted back to the Main Injector at the end of beam compression. The emittance of the beam at the beginning of merging was 18 eVs and at the time of extraction back to Main Injector was about 20 eVs with about 11% emittance dilution. The beam compression was very successful. Wall current monitor data during 2:1 beam compression from 1.6 usec to 0.8 usec (fig. 2) shows good agreement with ESME calculations shown in Figure 3.

Figure 4 shows the WCM data for beam expansion. The beam is expanded by a factor of 1.5.

Figure 5: Wall current monitor (WCM) data taken during bunch compression in the Main Injector. The data is taken with 10 msec/trace. The time goes from bottom to top for injection to extraction.
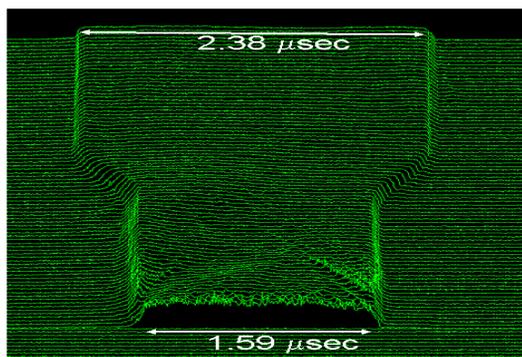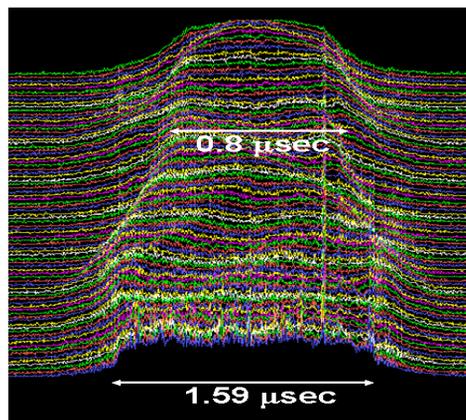

Figure 4: Wall-current monitor data taken during batch expansion from 1.59 usec to 2.4 usec in the Recycler. The time goes from bottom to top for injection to extraction.

SUMMARY AND CONCLUSIONS

Here we have proposed and demonstrated with beam experiments a new method for beam compression and expansion using barrier RF system. The experiments in the Recycler showed good preservation of longitudinal emittance through the process.

ACKNOWLEDGEMENT

Experiments at the Main Injector

Initial tests of this technique were also performed in the Fermilab Main Injector. At the time, performance was limited by a broadband kicker which could only produce, with limited fidelity, +/-500V waveform which was a factor of four smaller than that available in the Recycler. In addition, at the time the Main Injector lacked a beam loading compensation circuit for the 53 MHz accelerating cavities which are the dominant impedance in the machine. The basic beam compression operation was nonetheless partially successful. Figure 5 shows the WCM data from the beam compression experiment in the Main Injector. As expected we observed significant beam penetration into the barrier. However, one can see all features of beam compression.

Following the initial tests, two sets of dedicated broadband RF cavities have been installed in the main Injector: one rectangular-pulse system with a peak voltage of +/-10 kV [8], and another +/-1.5 kV arbitrary-waveform system [9]. A 53 MHz beam loading compensation circuit has also been installed. We plan to pursue these experiments and study the feasibility of this scheme for increasing the proton beam on antiproton and neutrino targets.

REFERENCES

[1] D. Boussard and Y. Mizumachi, CERN-SPS/ARF/79-11; IEEE PAC1979; K. Koba et al., Proc. of PAC2003 Conference, page 1736.

[2] J.E. Griffin et al., IEEE, Trans. Nucl., Sci., NS-30, 3502 (1983).

[3] Main Injector Technical Design Hand Book, 1994.

[4] G. Jackson, Fermilab-TM-1991, November, 1996.

[5] D. Callahan et al., "Longitudinal Beam Dynamics For Heavy Ion Fusion", IEEE PAC93, page 730.

[6] J. A. MacLachlan, HEACC'98, Int. Conf. on High Energy Accelerators, Dubna, Sept. 1998; J. A. MacLachlan, Fermilab Report No FN-529, (1989) (Unpublished); http://www-ap.fnal.gov/ESME/.

[7] J.E. Dey and D.W. Wildman, IEEE, Proc. the 1999 Part. Accel. Conf. New York, NY, 869, 1999).

[8] W. Chou et al., IEEE PAC03, P.2922

[9] G.W. Foster et al., "Bunch-by-Bunch Digital Dampers for the Fermilab Main Injector and Recycler", IEEE PAC 2003, page 323.