ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPMA044

BARRIER SHOCK COMPRESSION WITH LONGITUDINAL SPACE-CHARGE*

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Abstract

Synchrotrons and storage rings routinely employ RF barrier buckets as a means of accumulating charge to increase the peak intensity and preserve longitudinal emittance while minimizing emittance growth [1-3]. This was shown in the main injector and recycler at Fermilab as well as the SIS-18 at GSI Helmholtz center for heavy ion research. The RF cavities typically used are ferrite loaded magnetic alloys with low Q to maximize bandwidth and generate single pulses, either as delta functions, triangular or half/full period sine waves.

The University of Maryland Electron Ring (UMER) group is studying a novel scheme of bunch compression in the presence of longitudinal space charge. It has been analytically shown through 1-D computations that the presence of space-charge considerably improves the efficiency of the barrier compression by taking advantage of the shock-front that launches when the barrier moves into a space-charge dominated beam. In this paper, we summarize the initial results of the study.

INTRODUCTION

The University of Maryland Electron Ring is a storage ring that accesses high intensities through the use of low momentum high-current electron beams. The machine is capable of injecting various beam currents ranging from 0.6-to-104 mA (shown in Table 1) and has since propagated a new low current beam of approximately 50 μA in Nov 2014 [4]. This beam is still undergoing full characterization.

Table 1: Beam Parameters vs Injected Current

Current (mA)	Emittance (mm-mr)	c_s (1×10^6 x m/s)
0.05	TBD	0.066
0.6	7.6	0.285
6.0	25.5	0.766
21.0	30.0	1.27
78.0	58.9	1.90
104.0	64.0	2.03

Longitudinal space-charge causes the ends of the beam to axially expand, filling the ring with charge [5-6]. In order to overcome the longitudinal space-charge forces, a barrier bucket system was developed to prevent the expansion, allowing us to store the beam for more than 1000 turns [5]. The barrier bucket system consists of two independently operated burst mode modulators, where the first modulator applies an 8 ns FWHM negative voltage pulse to the head of the bunch and the other applies the equivalent positive pulse to the tail of the bunch. Both modulators are synchronized to injection and operate at the revolution frequency of the beam. Figure 1 below illustrates the voltage pulses (red), the beam current (black) from the wall current monitor in the ring as well as the synchronization between them. Note in this figure the voltage pulses are applied every fifth turn.

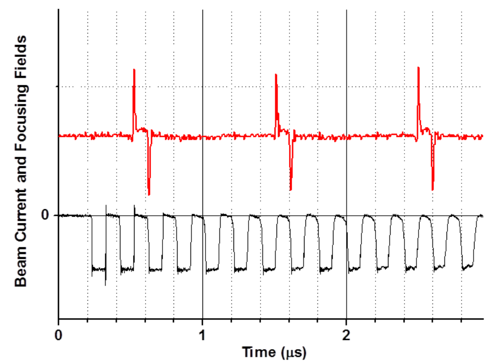

Figure 1: Synchronization between the barrier bucket fields (red) and beam current (black) from the wall-current monitor in the ring.

Once the barrier bucket fields are initiated, the beam can be stored for as long as required for a given experiment, limited by the average power that the pulse modulators can drive the low Q cavity. The modulators are capable of storing the 0.6 mA beam for more than 1000 turns. The barrier fields are not perfectly matched to the beam edges, resulting in space-charge waves induced at the edges of the beam that bounce from edge to edge during a long store of charge [5].

Various barrier bucket compression schemes have been explored in the past, to produce more intense beams for neutrino based programs demanding high intensity hadron beams [1]. A few schemes that have been explored are: barrier flip-flop, adiabatic compression and momentum stacking. Each of these schemes compresses the total charge in order to increase the peak current with little consideration for longitudinal emittance growth and especially when intense longitudinal space-charge forces are considered.

This paper summarizes both the computational and experimental progress on this novel method of compression with intense space-charge.

NOVEL METHOD OF LONGITUDINAL COMPRESSION

This method of compression utilizes longitudinal space-charge to assist with the compression of the beam,

*Work supported by the US Dept. of Energy, Office of High Energy Physics.

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by inducing a shock-front within the beam [7]. The benefit with this scheme is that the beam is not rotating in longitudinal phase-space, minimizing longitudinal emittance growth. The compression is performed by moving one of the barrier pulses into the beam to induce a shock-front while keeping the other barrier stationary, though in principle the compression could be performed from both ends simultaneously. We focus on the simplified case initially.

Experimental Results

The compression on UMER was performed by moving the tail barrier pulse into the beam at a rate of 0.5 ns/turn and keeping the head barrier fixed. Figure 2 below illustrates the beam current for the 0.6 mA beam for over 45 turns. The beam current is plotted every fifth turn up to turn 45 and shifted vertically by 0.5 mA.

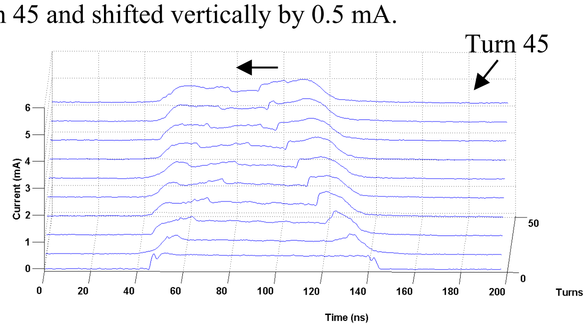


Figure 2: Beam current with compression at a rate of 0.5 ns/turn.

At this compression rate, the shock-front that develops in Figure 2, is very small in amplitude. At the final turn shown in Figure 2 turn 45, the peak current is 0.87 mA from the baseline. The peak current continues to increase as the bunch is further compressed.

Figure 3 below illustrates the beam current at an increased rate of compression, 1.0 ns/turn. The beam current is plotted every fifth turn up to turn 45 and shifted vertically by 0.5 mA as in the previous figure.

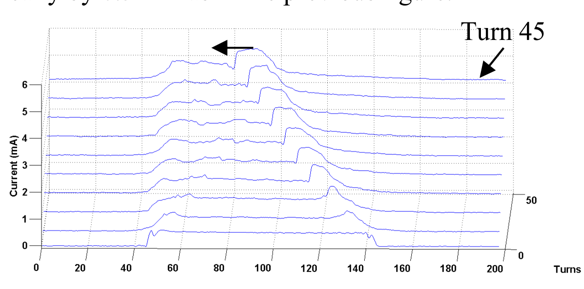
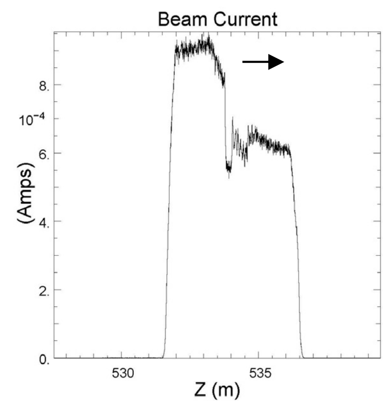


Figure 3: Beam current with compression at a rate of 1.0 ns/turn

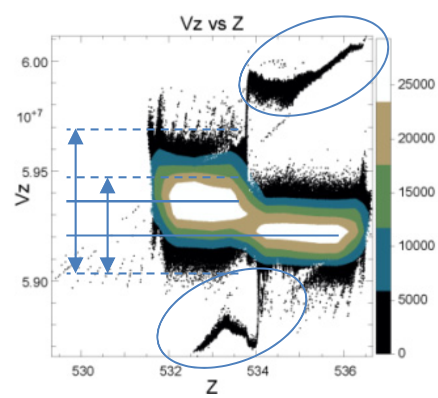
The shock-front that develops at the increased rate of compression is well defined compared with the previous case. At the final turn shown in Figure 3 turn 45, the peak current is 1.17 mA from the baseline.

Simulation Results

The same experiment was replicated in PIC simulations for the same 0.6 mA beam using WARP [8]. The simulation (shown in Fig. 4a-b) shifts the tail barrier field at 0.5 ns/turn while keeping the other fixed. Figure 4a illustrates the current profile versus z at turn 45 and figure 4b illustrates the longitudinal (v_z-z) phase-space at the identical turn. This differs from the experimental results as they are plotted in time whereas the simulation results are plotted in z.



(a)



(b)

Figure 4a-b: (a) – Beam current at turn 45, at a compression rate of 0.5 ns/turn. (b) – Longitudinal (v_z-z) phase-space at the same compression rate.

The peak current at this rate of compression is 0.9 mA at turn 45 (as shown in Fig. 4a). The peak compressed current agrees very well with the experimental results presented earlier in figure 2. The longitudinal phase-space (shown in Fig. 4b) resolves the shock-front in the middle of the beam as well as the formation of solitons (circled in Fig. 4b). The region of higher current within the bunch has a larger velocity spread propagating at $5.935x10^7$ m/s while the lower current region of the bunch has a lower velocity spread and propagates $1.5x10^5$ m/s slower at the injected velocity of $5.92x10^7$ m/s.

The following simulation (shown in Fig. 5) increases the rate of compression to 1.0 ns/turn.

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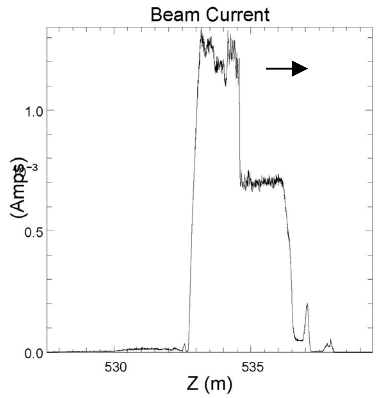

Figure 5: Beam current at turn 45, at a compression rate of 1.0 ns/turn.

At this rate of compression, the peak current increases to 1.25 mA at turn 45 (as shown in Fig. 5). This peak compressed current agrees very well with the experimental results presented earlier in Figure 3.

CONCLUSION

We summarize the initial results of a novel means of longitudinal compression on UMER. This method utilized longitudinal space-charge to assist with the compression of an intense beam by inducing a shock-front within the beam [7]. This scheme benefits from the fact that it does not require precise compression waveforms such as with longitudinal tilt compression commonly used in ion machines.

Additional parametric studies are required to optimize and tailor the applied fields to the beam-ends as well as understand the limitations of this method of compression. Limiting factors such as: what are the optimal rates of compression for a given beam current, what happens when the shock-front collides into the stationary barrier, what are the limitations when compression is applied from both ends of the bunch.

ACKNOWLEDGMENT

We would like to thank Oliver Boine-Frankenheim for his support of this work.

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