LONGITUDINAL BEAM BUCKET STUDIES FOR A SPACE-CHARGE DOMINATED BEAM

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Abstract

The containment of beams in the longitudinal direction is fundamental to the operation of accelerators that circulate high intensity beams for long distances such as the University of Maryland Electron Ring (UMER); a scaled accelerator using low-energy electrons to model space-charge dynamics. The longitudinal space-charge forces in the beam, responsible for the expansion of the beam ends, cause a change in energy at the beam head/tail with respect to the main injected energy or flat-top part of the beam. This paper presents the first experimental results on using an induction cell to longitudinally focus the circulating beam within the UMER lattice for multiple turns.

INTRODUCTION

High intensity particle beams are of interest in many accelerator applications that require a high quality beam transported over a long distance [1-3]. When beams are born from a low energy high current source, they are space-charge dominated [4]. The performance within the accelerator depends on the quality of the beam throughout the machine both transversely and longitudinally.

The defocusing space-charge force in the direction of propagation is the longitudinal electric fields generated at the edges of the beam from the gradient in line-charge density [5, 7]. Without any force in the longitudinal direction to contain the beam, similar to the forces in the transverse direction from quadrupoles and solenoids used to contain the beam transversely, a defocusing effect will become measurable after some given time during the beam's lifetime. This period of time is determined by the sound speed of the beam and the initial duty cycle of the storage ring [5]. If allowed to freely expand and eventually merge on itself, the beam will become "DC" to all the "AC" coupled detectors in the ring and become undetectable [6]. This poses a restraint on the physics that may be studied and so understanding how this effect operates and reduces the quality of the beam, is important when controlling it.

FOCUSING CELL

The longitudinal electric fields are placed at the beam ends using an induction cell installed at Ring Chamber-4 (RC4), 3.74 m from the gun as shown in Figure 1.

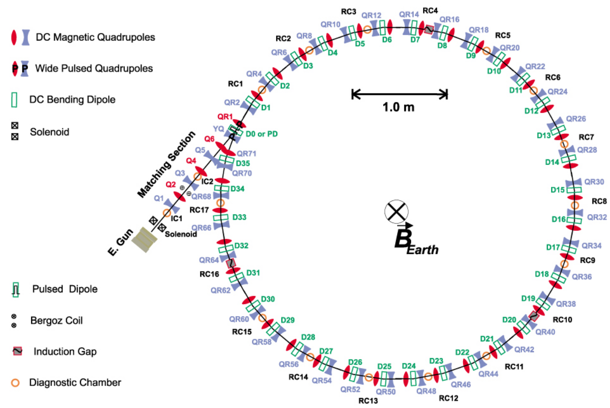

Figure 1: Ring Diagram.

The induction cell adds an inductive element in parallel with a resistive element across an electrical break within the beam pipe, called the glass gap [6]. As long as the modulator provides a time-varying source then a voltage drop will be induced across the glass gap. Figure 2 displays the potential across the glass gap.

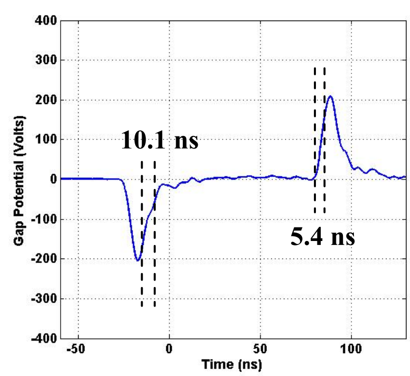

Figure 2: Gap potential as a function of time for both the decelerating and accelerating focusing field.

The beam is placed inside of the bucket, with zero potential across the gap, so the main beam energy is not affected and only the ends are.

FOCUSING SCHEDULE

The location and timing where focusing should be applied is decided based on the match of focusing fields to the beam head and tail widths shown in Table 1. From one-dimensional theory in Figure 3, the non-zero on-axis self-electric field at the edges of the beam, accelerate head electrons away from the main beam as well as decelerate tail electrons away [5-7].

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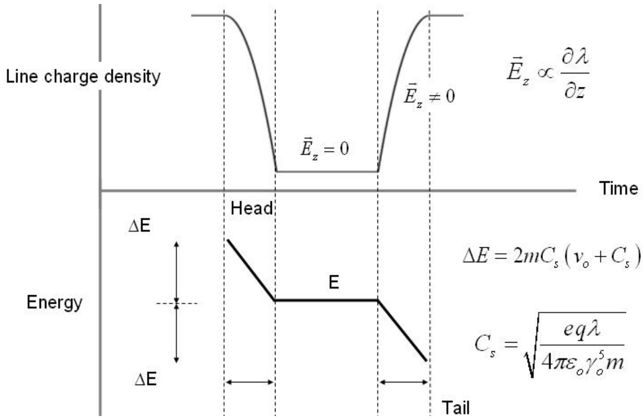

Figure 3: Line charge density and beam energy.

The difference in electron energy at the head or tail is given by twice the sound speed of the main beam [5-7].

The head and tail widths, in Table 1, are slightly different due too two reasons. Since the head is moving faster then the tail and current is the product of velocity and line-charge density, the current in the head will appear to be more linear and the tail more parabolic. This has a direct effect on the measured widths. The second reason is the different rise and fall time associated with the gun pulser driving electronics.

Table 1: Pencil beam head fall / tail rise times.

Turns	Head fall (ns)	Tail rise (ns)
0	1.1	1.3
1	5.8	2.8
2	7.9	5.6
3	9.8	8.0
4	11.8	10.2
5	14.0	11.4

Using the induction cell at RC4, we want to match the field width to the beam head/tail width. For the preliminary experiments that follow, the beam was captured on the 2nd turn.

From this data, the average experimental expansion rates may be calculated; 2.58 ns for the head and 2.06 ns for the tail. If focusing was applied to the head and tail on the 2nd turn, calculations suggest that the reapplication of the focusing fields would not need to happen until the 7th or possibly 8th turn, depending on the erosion rate. From the experimental results of single capture focusing on the second turn shown in Figure 4, the beam ends return to the initial width within approximately 5-to-6 turns from the point of initial focus.

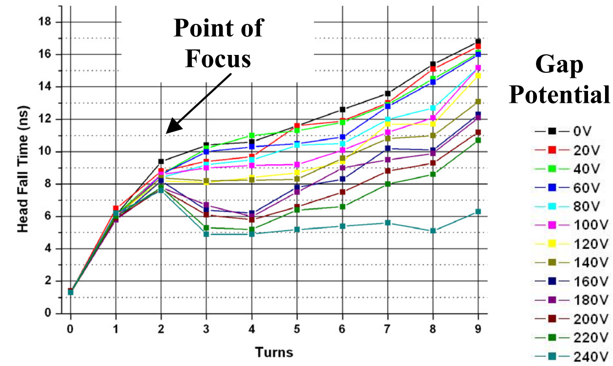

Figure 4: Beam head fall times with single application of focusing on 2nd turn as a function of turns and Gap potential, measured at RC10.

Figure 4 displays the experimentally measured beam head fall times as a function of turns and potential at Ring Chamber-10 (RC10) 7.58 m away from the gun. Using the beam size measured at Ring Chamber-3 (RC3), 3.1 m away from the gun, we attain a spread of possible focusing field's 160 – 193 v. Since we measure current down stream of the induction cell, located at RC10 and focus at RC4, we must account for the 0.86 ns growth from RC4-to-RC10 for the head.

Because of device limitations in the selection of synchronized burst frequencies to beam revolution frequencies, a specific burst frequency was selected and the beam circulation time was varied. Figure 5 displays the sweep as well as the extreme cases when the tail field or head field is inside the beam and the other is outside the beam. The extreme points are when the beam is revolving faster then the burst or the burst is faster then the beam.

The beam fields are synchronized to the beam when the beam energy is 10135.1 eV. This given energy corresponds to the (5 beam pulses-to-1 burst pulse) 1.0208248 MHz burst frequency or a beam revolution frequency of 5.1041241 MHz.

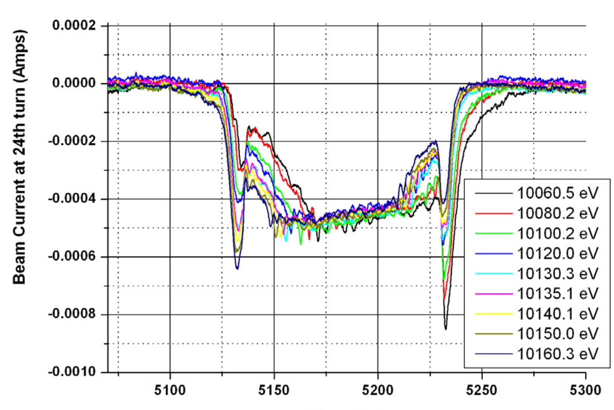

Figure 5: Beam current measured on the 24th turn at RC10, as function of swept energy.

PRELIMINARY EXPERIMENTAL RESULTS

Multi-turn focusing requires that the beam be focused periodically at some given period of time, namely the time it takes the beam to contract and then relax back to the initial length, at the time of the initial application of the focusing fields. Calculations and experiments suggest that this period be every 5-to-6 turns. The experimental results shown in this paper, report a focusing rate of every 5 turns.

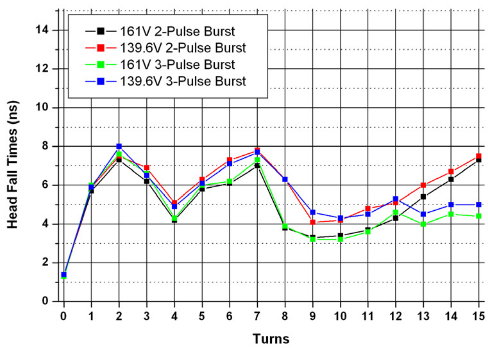

Figure 6: Beam head fall times measured at RC10.

The experiments were performed with a 2-pulse burst and a 3-pulse burst at two field amplitudes, 161 v and 140 v. The 2-pulse burst shows the minimum beam head contracting at the 4th turn and relaxing by the 7th turn. The fall time, at the 7th turn for the head is 7.8 ns as measured at RC10. If we use the 0.86 ns growth between RC4 to RC10, then the beam head length is 6.94 ns which is a 68.7 % match to the actual focusing field. After the second application of focusing on the 7th turn, the beam contracts again but doesn't relax to the correct width within the 5 turns. By the 12th turn the beam fall time is 4 ns at the induction cell. This is now a 43 % match to the field. If focusing is applied again on the 12th turn as shown for the 3-pulse burst, the beam head doesn't respond well but begins to create overshoots in the beam current as shown in Figure 7.

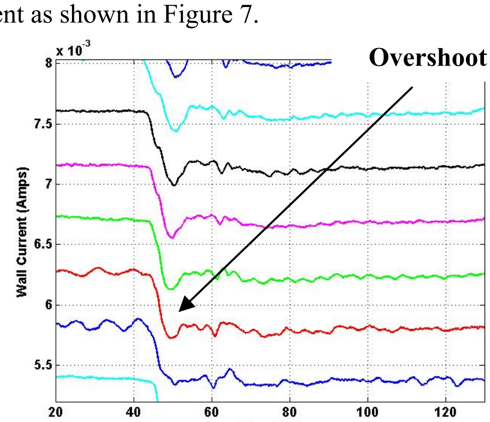

Figure 7: Overshoots in beam current measured at RC10.

With the mismatch between fields and beam edges, the beam continues to erode in the middle of the bunch. If the focusing is extended for eight applications, as in Figure 8, the beam is prevented from expanding.

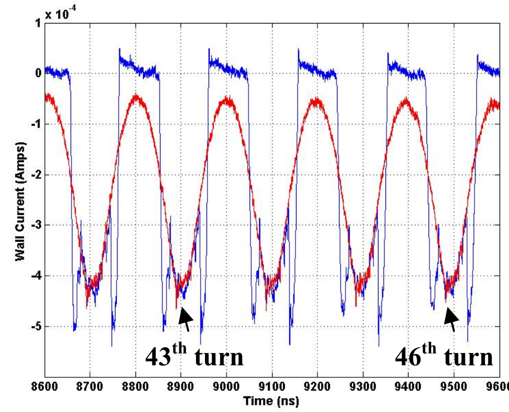

Figure 8: Long term effects of longitudinal focusing (Red-no focusing, Blue- with focusing).

The red signal (no focusing) in comparison with the blue signal (focusing) clearly shows the merging of the line charge density and the reduction of the detectable peak current at the 46th turn. In contrast, with the focusing system on we are able to keep the pulse approximately rectangular and detectable for a longer period of time in the ring.

CONCLUSION

The difficulty with longitudinal focusing is matching the fields to the beam at correct points as it propagates in the ring. The two main problems are; the initial point where the fixed width fields are placed and the refocusing rate of the applied fields. Even though field matching is an issue, propagation of the pencil beam can still be further extended with the focusing system set to these conditions. When longitudinal focusing is turned on for a long period of time on the pencil beam, such as 45 applications or 45 μs, the period of beam propagation has been shown to extend the pencil beam beyond 225 turns or 2.6 km; a factor of 2 greater then without focusing.

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