SPACE-CHARGE EFFECTS IN BUNCHED AND DEBUNCHED BEAMS

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Abstract

The University of Maryland Electron Ring (UMER) is a machine designed to study high-intensity beam physics. With the application of axial fields to the bunch ends, we are able to keep a beam with an injected tune shift of 1.0, bunched over multiple turns. This is feasible with the application of tailored fields to optimally match the space-charge self-fields while minimizing the excitation of longitudinal space-charge waves. With this scheme, we have been able to extend the number of turns at the University of Maryland Electron Ring (UMER) by a factor of ten. Without the use of longitudinal focusing, head and tail effects begin to dominate, especially with the higher current beams. Time resolved measurements of the peak correlated energy spread have shown in some cases a change in the overall spread of 1.8% for the 0.6 mA beam, from the injected beam energy.

INTRODUCTION

In the last century, the focus for particle accelerators has been on the frontier of high energy physics [1-4]. Now the frontier is shifting from high energy to high intensity, where the interest in accelerators requires the acceleration of a large number of particles that are contained in all six dimensions of phase-space [5-8]. This imposes stringent requirements on accelerator facilities to demand high quality beams, by minimizing both the transverse emittance and longitudinal energy spread while still maintaining a high-intensity beam. As examples, the Linac Coherent Light Source (LCLS) at Stanford and Inertial Fusion Energy production both require a minimization of the longitudinal energy spread in order to maximize efficiency of both the undulator and the power deposited on target, in each of the applications [9, 10].

This paper presents the latest results of the use of induction focusing to minimize the correlated longitudinal energy spreads at both the head and tail of the bunch in order to keep the beam bunched over a long path-length; preventing the beam from longitudinal filling the ring with charge. Under conditions of over focusing, space-charge waves induced at the bunch edges may be used to estimate the beam size.

LONGITUDINALLY DEBUNCHED BEAMS

When no external fields are used against the repulsive longitudinal space-charge fields, the coasting beam injected into the UMER lattice, longitudinally debunches (as shown in Fig. 1). Space-charge accelerates particles in both the head and tail of the bunch from the injected energy.

The outermost edge of the bunch head theoretically has particles with energies of $\frac{1}{2}m\left(\mathrm{v}_o+2C_s\right)^2$, where $\frac{1}{2}m\mathrm{v}_o^2$ is the particle energy in the central region of the beam, m is the mass of an electron, v_o is the beam velocity and C_s is the sound speed of the beam.

The theoretical energy at the outermost edge of the bunch tail is $\frac{1}{2}m\left(\mathrm{v}_o-2C_s\right)^2$. This is explained in greater detail in Refs. [11-15].

The maximum measurable energy gained at the bunch head with the 0.6 mA beam over multiple turns is approximately 86 eV (measured from the 10% to 90% points of the current waveform). The bunch tail looses approximately 93.6 eV (10% to 90%). The overall change in energy across the length of the bunch is 1.8% of the injected 10 keV beam energy. Particle simulations and analytical calculations show good agreement with measurements [14].

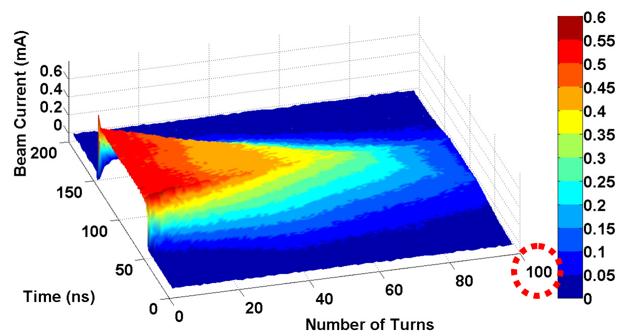

Figure 1: Three-dimensional view of the measured beam current at RC 10 as a function of the number of turns. Color bar indicates the peak current amplitude in mA. This displays the beam **without** longitudinal focusing.

Without the confinement fields applied periodically, the bunch longitudinally erodes resulting in approximately only a hundred turns of transport for the 0.6 mA beam (as shown in Fig. 1), filling the ring with charge by the 27th turn. As the beam fills the ring from the resulting longitudinal space-charge forces, the AC coupled wall current monitor effectively becomes blind to the DC background current. This results in what appears to be zero measurable current beyond that point. See reference [16] for further explanation on the topic of longitudinal relaxation.

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LONGITUDINALLY BUNCHED BEAMS

When longitudinal confinement is applied periodically (every 5 turns at 59.6 volts) to the bunch-ends of the 0.6 mA beam, the rectangular bunch shape is maintained over more than a thousand turns (as shown in Fig. 2).

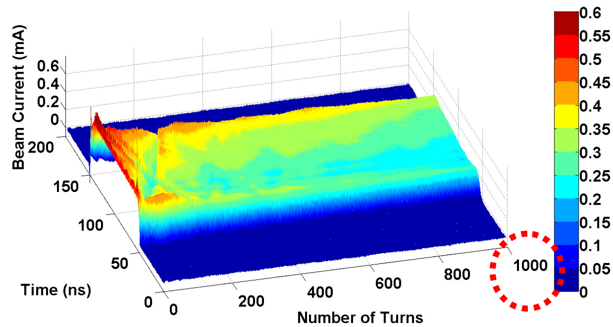

Figure 2: Three-dimensional view of the measured beam current at RC 10 as a function of the number of turns. Color bar indicates the peak current amplitude in mA. This displays the beam **with** longitudinal focusing.

We are able to propagate approximately 60% of the injected 0.6 mA, with a substantial loss of charge (approximately 18%) within the first 30-50 turns and a slower loss over the last 900 turns. The slow loss is believed to be a slow scraping of charge per turn, as if the beam transverse spot size has blown up. Figure 3 below, illustrates the charge contained with longitudinal focusing (in blue) as well as without (in magenta).

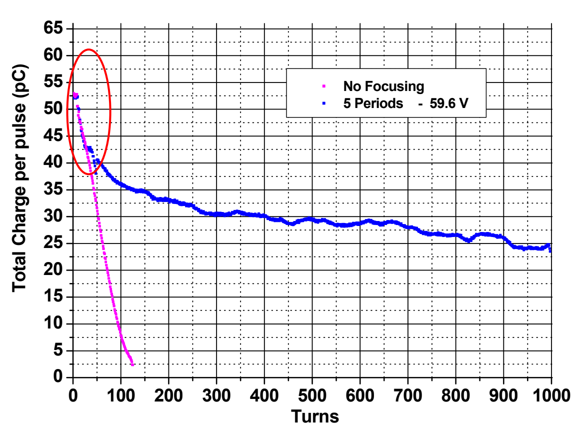

Figure 3: Total integrated charge measured from the RC10 wall current monitor with (in blue) and without (in magenta) longitudinal focusing.

The red oval (in Fig. 3) displays the region of charge loss in the beginning of transport that is independent of longitudinal focusing.

Using the space-charge waves induced at the bunch edges, we are able to estimate the beam size at the beginning of transport, allowing us to verify if in fact that the beam is blowing up, supporting a possible current loss mechanism.

Figure 4 illustrates the first 180 turns (shown in Fig. 2) with longitudinal focusing. Unlike Fig. 2, there is no interpolation between turns.

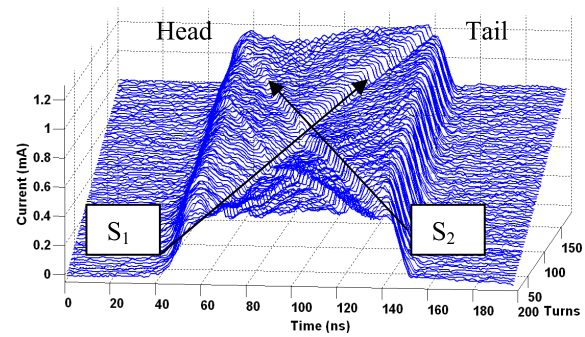

Figure 4: Individually measured beam current profiles per turn, displaying the waves launched from imperfections in the applications of the confinement fields. For clarity, starting from turn 21, each trace is shifted up by 0.01 mA from the previous turn.

The two space-charge wave propagating across the length of the bunch are identified as S_1 (slow wave) and S_2 (fast wave) on Fig. 4. If we fit the waves propagating along the bunch, we can measure the sound speed and estimate the beam size during the period of the wave.

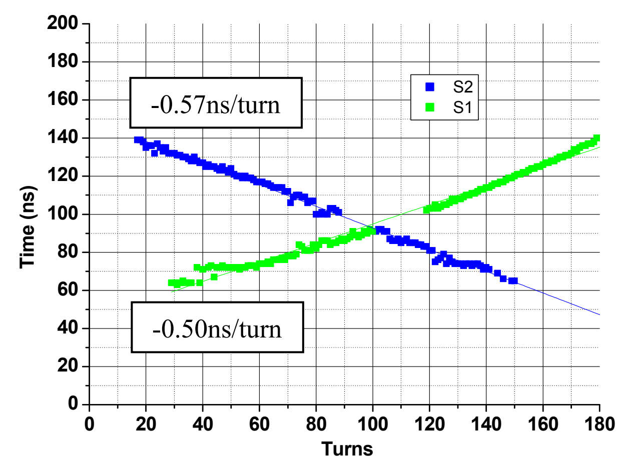

Figure 5: Measured wave positions within the bunched beam as a function of turns. Both S_1 and S_2 propagation rates (slopes) are given on the figure.

The slope for each wave is shown in figure 5. Using Eqn. 1 and 2, we are able to calculate the sound speed C_s and then the beam size, assuming the beam is emittance dominated.

$$C_s = slope \times {v_o^2}/{R} \tag{1}$$

$$a = \frac{b}{e^{\frac{2C_s^2 \pi \varepsilon_o \gamma^5 m}{q\lambda}} e^{-\frac{1}{4}}} \tag{2}$$

where R is the ring radius (11.52 m), b is the pipe radius (25.4 mm), ε_o is the relative permittivity, m is the electron mass, q is the electron charge, and γ is the relativistic factor and λ is the line-charge density.

Analytical calculations of sound speed for a 0.43 mA beam and injected beam radius of 1.56 mm, approximates a sound speed of $2.52\text{x}10^5$ m/s. The measured speeds of S_1 and S_2 are 1.49 $\text{x}10^5$ and $1.68\text{x}10^5$ m/s, respectively. This estimates a beam size between 11.31 and 8.44 mm, respectively. This is a factor of (5-7) growth in the beam size from the injected beam. Recent measurements using a vertical extractor at RC 6 on to a screen at RC 8, has indeed shown that there is a growth in size [16]. This bigger beam is most likely the cause for the initial current loss within the first 30-50 turns as a result of scraping along the accelerator pipe walls. Further experiments have also shown that this beam growth may be reduced by changing the operating point slightly, improving the current transmission within the first 500 turns.

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CONCLUSION

In this paper, we have presented that without longitudinal focusing, longitudinal space-charge forces cause the beam to elongate and eventually fill the ring with charge.

But, when longitudinal focusing fields are applied to the beam edges, we are able to keep approximately 60% of the beam bunched for many turns suffering from current loss within the first 30-50 turns. We have observed, under conditions of over focusing, space-charge waves induced at the bunch edges. Through measurements of the propagation wave speed (sound speed), we have estimated a transverse beam growth, which was confirmed by recent measurements of beam size. We have also shown that this growth can be reduced by varying the operating point slightly.

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