EXPERIMENTAL OBSERVATIONS OF LARGE-AMPLITUDE SOLITARY WAVES IN ELECTRON BEAMS*

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Abstract

The longitudinal dynamics of space charge dominated beams plays an important role in particle accelerators and other applications such as heavy ion fusion, spallation neutron sources and free electron lasers (FELs). All beams are space-charge dominated near the source [1]. By means of experiments on the University of Maryland Electron Ring (UMER), we studied how a perturbation to the line charge density could affect the beam propagation. By varying the initial amplitude of the perturbation, we access nonlinear space charge physics. When starting with large-amplitude perturbations, we have observed, for the first time in charged particle beams, solitary waves for which the nonlinear steepening exactly balances the wave dispersion, leading to persistent waves that preserves their shape over a long distance.

This paper presents the results of the soliton experiments, including systematic studies of the dependence of the soliton propagation on beam current, perturbation strength and width.

INTRODUCTION

High beam current and high beam quality are demanded in modern advanced accelerators [2, 3]. Understanding the space charge effects in such high brightness beams is pivotal for better accelerator designs and operations. In space charge dominated beams, the non-linear space charge force will introduce collective effects and limit the maximum beam current and beam quality. One of the collective effects that is not well understood is the longitudinal space charge waves [1] caused by perturbations on the beams. These perturbations could be generated by factors like fluctuations in beam current, either from the thermionic emission or photoemission, or the mismatch of the longitudinal focusing channels [4]. As a result, they could lead to beam instabilities and microbunching [5-6]. Therefore, it is important to understand the longitudinal dynamics of space charge dominated beams.

From previous study the space-charge waves [7-9], using the one-dimensional cold fluid model, it is shown that the initial perturbation will split into two space charge waves, a slow wave and a fast wave, which is also experimentally observed. However, things become more complicated when the perturbation goes into the nonlinear regime. Introducing a large-amplitude perturbation by a UV laser, we are able to observe the evolution of the space charge wave under nonlinear effects [10].

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UMER [11] is a world-class facility designed for exploring the physics of charge particle beams at the extreme frontier of intensity. As a scaled model to investigate the transverse and longitudinal dynamics of space charge dominated beams, it is a circular machine with a circumference of 11.52m. The electron beam has 10keV energy, 0.3-3um emittance, and 197ns circulation time. The beam bunch has up to 10^{11} particles, and the duration varies from 25 to 140ns.

THEORETICAL MODEL

To study the nonlinear theory of longitudinal space charge waves, the one-dimentional kinetic model is applied based on the Vlasov-Maxwell equations [12]. It is theoretically predicted that solitary waves, evolving according to the Korteweg-deVries (KdV) equations, could be generated on the beam with a large amplitude perturbation. In this model, several assumptions have been made: first, the beam intensity is sufficiently low to neglect the dependence of beam edge r_b and rms radius R_b on line density λ_b. Also, in the long wavelength limit, the axial line density varies slowly to satisfy $k_z^2 * r_w^2 << 1$, where k_z is the inverse length scale of z-variation, and r_w is the wall radius. By solving the differential equations in the kinetic model, we reduced to a KdV equation with the soliton solution:

$$\eta = \frac{3}{2}(M^2-1) * \sec h^2[\frac{1}{2}(M^2-1)^{1/2} * (Z-MT)]$$

Where η is the line density perturbation distribution, M is the pulse speed normalized to the sound speed, Z and T are the scaled spatial and time variables.

Theoretically, for a large-perturbation pulse, particles on the crest travel faster than the ones on the trough. Therefore, the beam steepens and breaks. When the pulse length is comparable with the pipe radius, the wave becomes dispersive [13] and it could balance the nonlinear steepening effect, which finally leads to solitons.

EXPERIMENTAL SETUP

The UMER gun is a thermionic dispenser cathode, made of a porous tungsten (W), coated with barium oxide and calcium aluminate. It could operate in the current range of 0.6 to 100mA.

The gun could also generate beams by photoemission [14], which we apply to introduce the perturbation on the beam. We use a 1064 nm-wavelength Nd-YAG drive laser and triple its frequency with two nonlinear crystals to a wavelength of 355nm [Fig. 1], making the photon energy sufficient to generate photoemission from the cathode. The perturbation is usually 5-8ns wide and it takes about 10 turns in the ring for the pulse to propagate from one edge to the other on the 100ns-wide base beam.

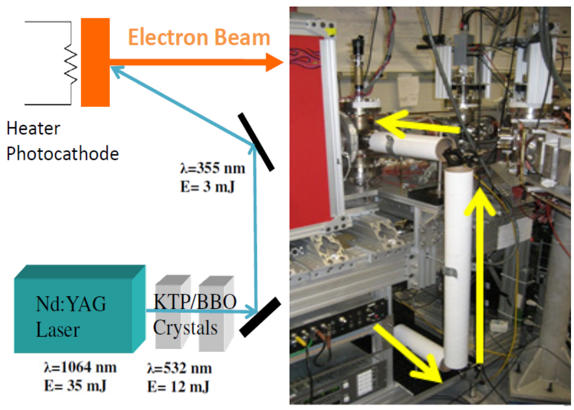

Figure 1: Schematic of the perturbation experimental setup (left) and the real setup in UMER lab (right).

The laser is injected into the chamber (IC1), where it will be reflected by a dielectric mirror towards the photocathode. The initial condition of the beam with perturbation will be measured at the Bergoz, a fast current transformer placed 64cm from the electron gun aperture. The multi-turn beam measurement is taken by a wall current monitor (RC10) inside the ring, which is 7.67m from the Bergoz.

We systematically tried different parameter values: beam current from 20 to 40mA, perturbation level from 20% to 70%, and perturbed pulse width from 5ns to 10ns. Solitons are observed and their dependence on the parameters is also studied.

EXPERIMENTAL RESULTS

Figures 2 and 3 are typical experimental results of a nonlinear density perturbation on the beam. In Fig. 2, the initial condition at the Bergoz is 22mA beam with 50% perturbation. The perturbation is introduced near the tail of the beam to allow the fast wave to spend a longer time in the flat-top portion of the beam. Fig. 3 depicts the turn-by-turn beam current measured at RC10. The fast wave moves left while the slow wave steps off the beam edge since the perturbation splits at the first turn. For better comparison, the beam current is shifted upward by 20mA on the plot after every turn. It could be seen that the fast wave steepens and breaks into several sub-pulses. Starting from about the 4th turn, the sub-pulses maintain their shape (amplitude and width) when propagating in the beam frame, which is a basic property of soliton.

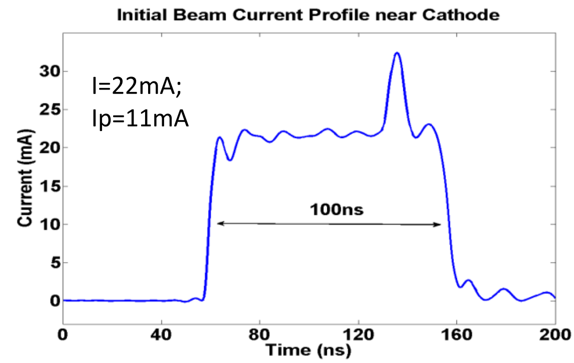

Figure 2: Initial beam condition measured at Bergoz.

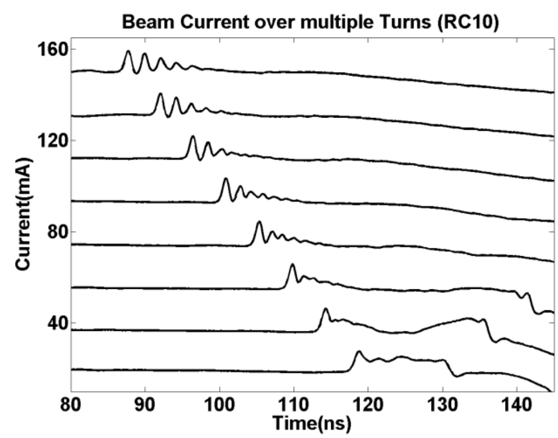

Figure 3: Turn-by-turn plot of beam propagation at wall current monitor (RC10).

To study the soliton dependence on the beam current, perturbation strength and beam width, we changed one parameter at a time and then do the turn-by-turn plot comparison. Results are shown from Fig. 4 to Fig. 6.

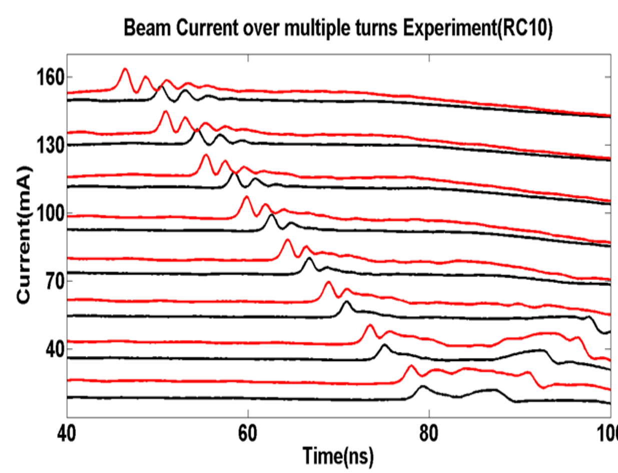

Figure 4: Turn-by-turn plot comparison between 23mA beam (black) and 30mA beam (red), both with 20% perturbation and 5ns width.

In Fig. 4, we did a 23mA vs 30mA beam experiment, with the same perturbation level (20%) and pulse width (about 5ns). The 30mA case has a faster wave breaking and more sub-pulses are generated. It should be due to the faster sound speed, which is proportional to current density. Also, we observed that if the beam current is below certain threshold value (around 20mA in UMER), then no solitons could be generated.

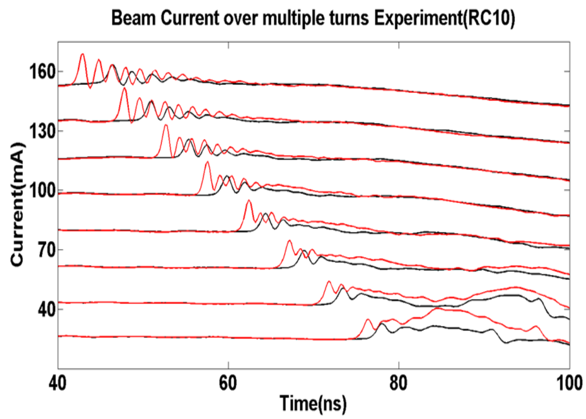

Figure 5: Turn-by-turn plot comparison between 20% perturbation (black) and 50% perturbation(red), both with 30mA perturbation and 8ns width.

In Fig. 5, we studied the perturbation strength dependence. As can be seen, different perturbation levels cause big differences on the result. The 50% perturbation case propagates faster and gives more sub-pulses compared with the 20% perturbation case.

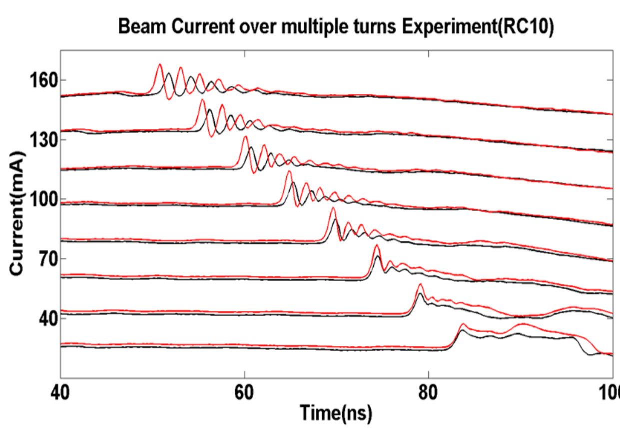

Figure 6: Turn-by-turn plot comparison between 6ns wide perturbation (black) and 8ns wide perturbation (red), both with 30mA beam and 50% perturbation.

In Fig. 6, we tried different perturbation pulse width, one 6ns, the other 8ns. Since they have the same beam current and perturbation level, their sound speed is very close. But a wider pulse results in more sub-pulses, which could be due to less dispersive effect.

All the results of the soliton dependence experiments agree well with the theory qualitatively. Quantitative work is expected in the future for the study of soliton dependence.

CONCLUSION

An experimental study of large-amplitude perturbations on an intense electron beam is presented. We successfully observed solitary waves in the beam frame and demonstrated an advantage of studying solitons on particle beams is the ability to generate solitons over a wide range of parameters, to control the propagation precisely and track them for a long distance.

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