EXPERIMENTAL OBSERVATIONS OF A MULTI-STREAM INSTABILITY IN A LONG INTENSE BEAM

B.L. Beaudoin, S. Bernal, I. Haber, R.A. Kishek, T. Koeth, University of Maryland, College Park, MD 20742, USA

Abstract

We have observed evidence of a multi-stream instability in a long non-relativistic space-charge dominated beam in the University of Maryland Electron Ring (UMER). The initial bunch is injected to fill a fraction of the ring and coast without longitudinal containing fields (or RF). The longitudinal space-charge forces in these intense beams cause it to expand axially and wrap the ring multiple times. The velocity separation between the wrapped filaments decreases as the bunch propagates. The onset of the instability occurs when the separation between filaments is equal to a longitudinal wave speed, c_s. This has been observed experimentally and compared with analytical calculations as well as Particle-In-cell (PIC) simulations, with good agreement. The onset depends on the injected beam current, fill factor, and other experimental conditions.

INTRODUCTION

Stream instabilities are a common feature in charged particle beam systems, such as between ion beams and background electrons or multi-bunch single species beams, where there the macro pulse is a compilation of short bunches [1-6].

We discuss simulation and experimental measurements of a streaming instability observed to result from the free expansion of a coasting rectangular bunch in a storage ring. We obtain good agreement with simulations when the measured transverse loss rates of the beam are included in the model.

Longitudinal Erosion

The coasting beam, injected into UMER, debunches due to longitudinal space-charge forces and evolves with a velocity profile as shown in Fig. 1 [7]. The outermost edge of the bunch head/tail is predicted to have particles with velocities that are $\Delta v = \pm 2c_s$ above/below the main beam velocity of v_o; where the longitudinal wave speed is defined as $c_s^2 = qg\lambda_o/4\pi\varepsilon_o\gamma_o^5 m$, m is the electron mass, q is the electron charge, γ_o the Lorentz factor, λ_o the line-charge density, ε_o the permittivity of free space and the variable $g = 2\ln {}^{b}/_{a}$ is the geometry factor accounting for the pipe shielding of the longitudinal self-fields in a pipe of radius b with a beam of radius a [8-9].

Both the head and tail of the beam continue to elongate and wrap the circumference of the machine at a rate of $4c_s$. As the bunch continues to wrap, the velocity separation between filaments decreases and approaches a longitudinal wave speed, c_s.

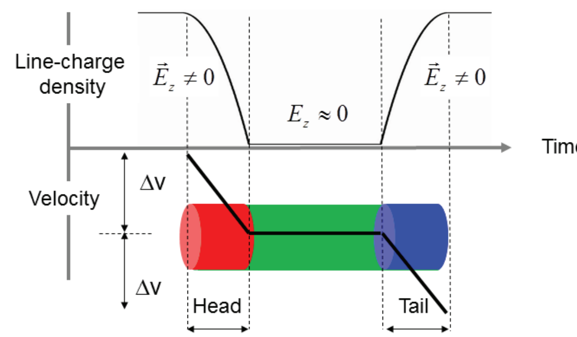

Figure 1: Illustration of the line-charge density and velocity profile of an intense rectangular bunch. Longitudinal space-charge accelerates/decelerates particles in both the head and tail of the bunch from the injected beam velocity, v_o.

Onset of the Instability

The onset of instability occurs when the separation between the wrapped filaments is equal to a longitudinal wave speed, c_s[10]. The onset of the instability can be calculated using Eq. 1 derived in [10]:

$$s_{\text{onset}} = \frac{2v_o C}{c_s}|\eta - 1| \quad (1)$$

where s_{onset} is the beam propagation path length to the onset of the instability, C is the circumference of the ring (11.52 m), η is the unitless initial fill factor, $\eta = \tau_p/\tau_r$ the ratio of injected bunch length τ_p (in time) to the revolution period τ_r (197.39 ns). This formulation assumes no current loss over the distance the beam has propagated. The filament threshold may also be calculated using Eq. 2 derived in [10]:

$$M_{\text{thr}} = 8|\eta - 1| + \eta \quad (2)$$

The number of filaments at the onset of the instability, for a fill factor of 0.5, is 4.5. This number decreases with larger fill factors.

EXPERIMENTAL OBSERVATIONS

Multiple experiments were conducted to explore the onset of the instability over a broad range of beam parameters, including the injected current and fill factor. A resistive wall current monitor, 6.4 m downstream of the gun, is used to measure the current versus time for the

*Work supported by US Dept. of Energy, Office of High Energy Physics, and by the US Dept. of Defense, Office of Naval Research and the Joint Technology Office

ISBN 978-3-95450-122-9

various cases studied. Figure 2 below, illustrates a wall current monitor trace for a 6 mA 98.77 ns bunch with an initial fill factor of 0.5.

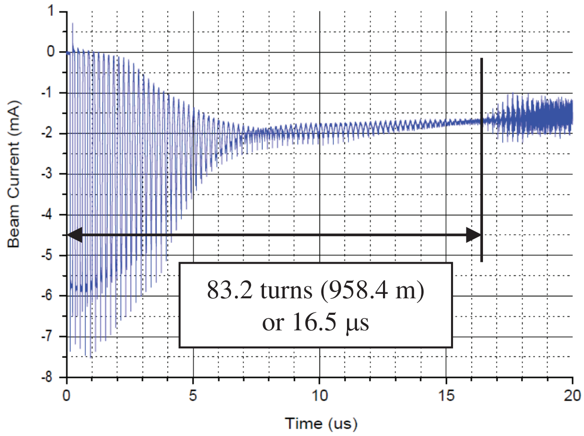

Figure 2: Measured current profile using the resistive wall current monitor, for the 6 mA 98.77 ns bunch with a fill factor of 0.5. Note the onset of the instability at 16.5 μs.

The onset of the instability occurs in 16.5 μs or 83.2 turns (958.4 m) for this particular beam current and fill factor. Further measurements in [10] have shown that the onset of the instability occurs sooner for larger fill factors as well as larger beam currents.

WARP SIMULATION

The instability is also observed under similar conditions in a PIC code WARP [11]. Simulations of the 10 keV beam were performed in a straighten model using an RZ field solver with periodic boundary conditions in the axial direction equal to the ring circumference. The number of cells in r and z was 64 and 256, with an approximate step size of 1.71 ns. The total number of macro-particles was 10 million. The three dimensional behaviour was otherwise ignored except when including the measured loss rates observed in the experiment over multiple turns [12-13].

Simulation without Loss Profile

Initially, no current loss simulations were performed in order to validate the theoretical framework of the instability observed in UMER. Figure 3 below, illustrates a no current loss simulation with multiple wrappings of the bunch after the beam has propagated 908.5 m in the ring. At this point the beam has an unwrapped length >6C, where the length of the z axis in the phase space plot corresponds to the ring circumference (11.52 m).

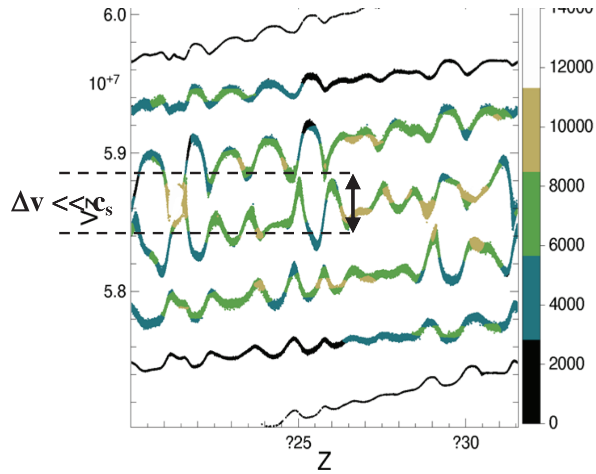

Figure 3: Simulated phase space image over multiple turns, wrapping the ring >6C for an injected bunch length of ΔL = 0.506C or fill factor of 0.506. The length of the z axis corresponds to the ring circumference. This simulation includes no current loss.

The simulation allows us to observe the longitudinal phase space images and the number of filaments that occurs at the onset of the instability. The modulated filaments, in Fig. 3, illustrate a well-developed instability. Figure 3, also illustrates that the separation between filaments is less than a longitudinal wave speed. At this point, the beam has >6 filamentations, corresponding to the fact that it is beyond the 4.5 threshold calculated previously using Eq. 2.

Simulation with Loss Profile

When current loss is included in the simulations, to better model the experiment, the onset of the instability is delayed from the analytical calculations as a result. This occurs as a result of the current dependent behaviour of the longitudinal wave speed. Deviations from the injected current, alters the erosion rate per turn and delays the onset of the instability.

We obtain good agreement with measurements of the onset when the carefully measured loss rates are incorporated into the simulation model [10].

CONCLUSION

We have shown both experimentally and computationally, a multi-stream instability occurs in a single long electron bunch propagating in a ring that is a function of both the initial bunch length (initial fill factor) and current. We also present the results of a simple theory, allowing one to predict the onset of the instability given no current loss. When current loss is accounted for in the simulation model, we obtain good agreement with measurements.

ISBN 978-3-95450-122-9

ACKNOWLEDGMENT

We wish to thank Alex Friedman, Dave Grote, and Jean-Luc-Vay for their support of the WARP code, as well as David Sutter, Ralph Fiorito, Massimo Cornacchia, Hao Zhang, Kamal Poor Rezaei, Yichao Mo, Will Stem and Kiersten Ruisard.

REFERENCES

[1] R.C. Davidson and H. Qin, Physics of Intense Charged Particle Beams in High Energy Accelerators (Imperial College Press, Covent Garden, London, 2001).
[2] R.C. Davidson, E.A. Startsev, M. Dorf, I.D. Kaganovich and H. Qin, Proc. 2009 Part Accel Conf, Vancouver (IEEE, New York, 2009), p. 1525.
[3] R.J. Macek, et al., Proc. 2001 Part Accel Conf, Chicago (IEEE, New York, 2001), p. 688.
[4] I. Hofmann, Part. Accel., 34, p.211-220 (1990).
[5] S. Appel, T. Weiland and O. Boine-Frankenheim, Proc. 2010 International Part Accel Conf, Kyoto (IEEE, New York, 2010), p. 1916.
[6] S. Appel and O. Boine-Frankenheim, Physical Review Special Topics – Accelerators & Beams 14, 054201 (2012).
[7] A. Faltens, E.P. Lee, and S.S. Rosenblum, J. Appl. Phys. 61, 5219, (2011).
[8] B. Beaudoin, I. Haber, R.A. Kishek, S. Bernal, T. Koeth, D. Sutter, P.G. O'Shea, and M. Reiser, Physics of Plasmas, 013104, (1987).
[9] B.L. Beaudoin, Ph.D. Dissertation, University of Maryland, (2011).
[10] B.L. Beaudoin, R.A. Kishek, I. Haber, and T. Koeth, "Experimental Observations of a Multi-Stream Instability in a Single Long Electron Bunch," Phys. Rev. Letts., submitted (2012).
[11] D.P. Grote, A. Friedman, I. Haber, and S. Yu, Fusion Engineering and Design, 32-33, 193, (1996).
[12] T. Koeth, B. Beaudoin, S. Bernal, I. Haber, R.A. Kishek, and P.G. O'Shea, Proc. 2011 Part Accel Conf, New York (IEEE, New York, 2011), p. 22.
[13] T.W. Koeth, B. Beaudoin, S. Bernal, I. Haber, R.A. Kishek, M. Reiser, and P.G. O'Shea, Proc. AIP Conf Proc, Annapolis (2010), p. 608.