OBSERVATIONS AND SIMULATIONS OF PARTICLE-DENSITY OSCILLATIONS IN AN APERTURED, SPACE-CHARGE DOMINATED ELECTRON BEAM*

S. Bernal[†], R. A. Kishek, M. Reiser,
Institute For Plasma Research, University of Maryland, College Park, MD
I. Haber, Naval Research Laboratory, Washington, D.C.

Abstract

Experiments and particle-in-cell (PIC) simulations in connection with the University of Maryland Electron Ring [1] demonstrate the appearance and evolution of transverse space-charge waves in a space-charge dominated electron beam. The waves are observed regardless of the focusing system, although the strength of the focusing affects their onset and evolution. An aperture induces the perturbation in the particle distribution in an initially freely-expanding beam. Simulations show that the effect of the aperture can be modeled approximately by a beam with an initially semi-Gaussian particle distribution with a temperature profile. Furthermore, simple tracking of test particles initially near the aperture's edge reproduce well the onset of the perturbation. For the parameters investigated, simulations further indicate that the perturbation damps out over a few plasma periods without causing any emittance growth.

Detailed understanding of the effects of space charge in the transport of intense beams is important in all areas of research and applications where beam quality is crucial. A rarely discussed aspect concerns the evolution of beams from the source to equilibrium, if any, including the role of source errors or aberrations, apertures and other factors that affect the initial particle distribution in phase space. The initial density profile of a beam has long been recognized as an important factor in determining its evolution (i.e., emittance growth, instabilities, etc.) [2]. A less appreciated influence on the dynamics is the initial temperature profile of the beam. For the Kapchinskij-Vladimirskij (K-V) distribution [3], Gluckstern [4, 5] has derived transverse kinetic oscillation modes that involve an exchange between the temperature and density profiles. However, since the K-V distribution is highly idealized, the Gluckstern modes, which can become unstable, have been thought not to exist for a physical beam. Using a warm-fluid model, Lund and Davidson [6] have rederived the Gluckstern modes and extended them to an arbitrary equilibrium distribution. Further, recent computer simulations by Lund et al. [7], relating to experiments at Lawrence Berkeley National Laboratory, exhibit density oscillations similar to Gluckstern modes, in a beam whose initial temperature or density profiles are perturbed. Despite the important insights provided by these studies, no clear connection has been established in either experiments or simulations between the physical cause(s) of the initial beam perturbation, the resulting phase-space distribution, and the long term evolution of this distribution.

This paper [8] presents concrete experimental evidence, augmented by self-consistent particle-in-cell (PIC) computer simulations, for the occurrence of wave-like transverse density oscillations in an electron beam. The beam is perturbed by an aperture near the source, giving rise to an initial distribution that is far from equilibrium around the beam's edge. Two transport experiments over a distance of about one meter and with similar overall focusing strengths (as given by the zero-current phase advance in the corresponding matched beams) demonstrate the onset and evolution of the beam perturbation.

Figure 1 shows the schematics of a transport experiment with three short solenoids of the type employed extensively at Maryland. The second experiment uses a solenoid and five printed-circuit (PC) air-core quadrupoles similar to the lenses introduced recently for the University of Maryland Electron Ring [1].

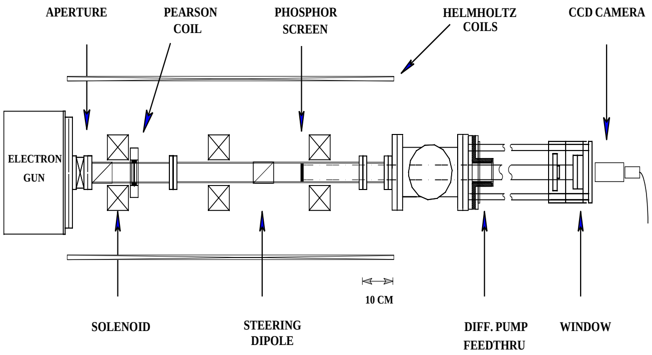

Figure 1: Three-solenoid experiment setup.

---

[*] Work supported by the U.S. Department of Energy.

[†] Email: sabern@glue.umd.edu

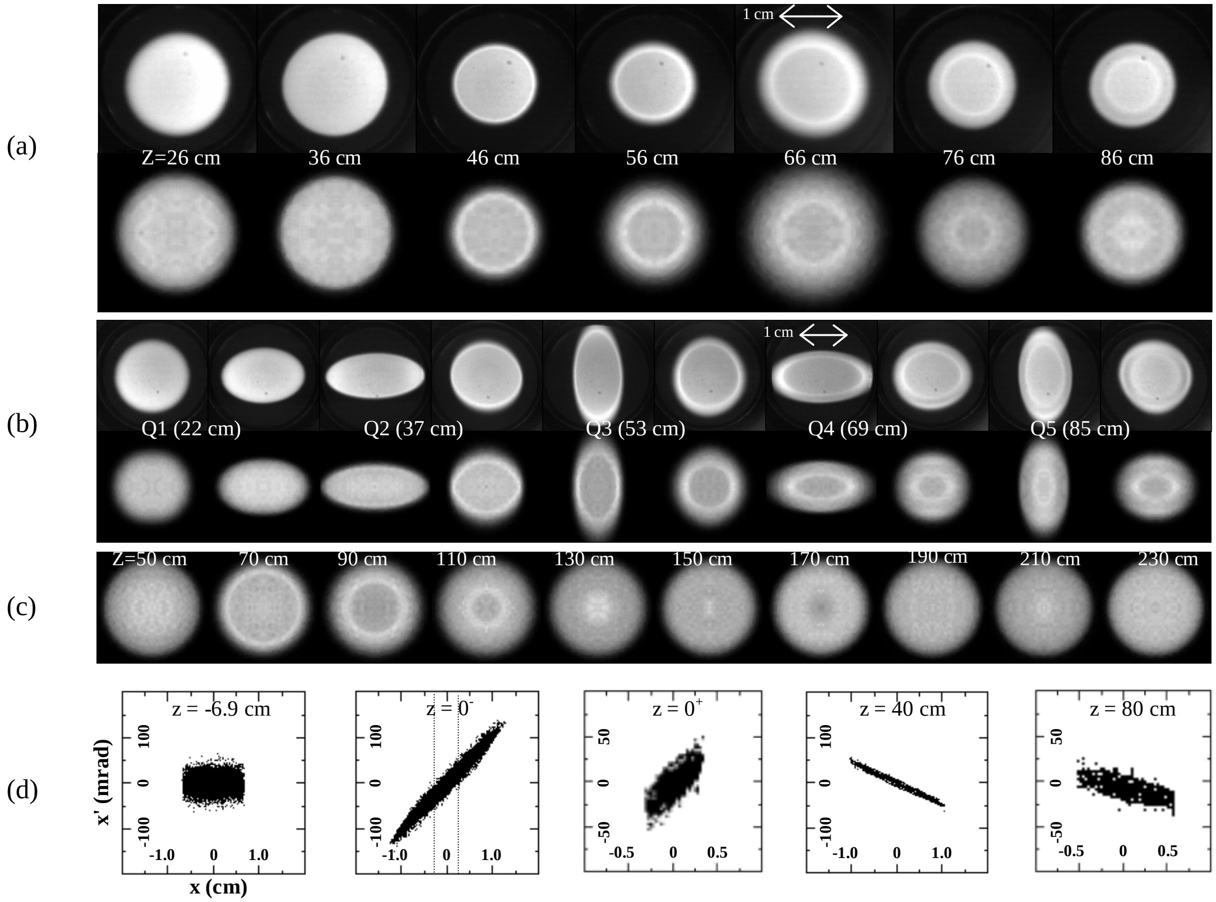

Figure 2: Summary of experiments and simulations: (a) three-solenoid experiment - phosphor screen pictures (top), and PIC simulations (bottom); (b) solenoid-five PC quadrupole experiment - phosphor screen pictures (top), and PIC simulations (bottom); (c) simulation of uniform focusing case, where the (matched) beam size is constant (0.8 cm in radius); and (d) horizontal projection of phase-space at (from left to right): the beam waist, the upstream plane of the aperture - the dashed lines indicate the 0.32 cm (radius) aperture - , the downstream plane of the aperture; the last two plots correspond to the solenoid-five quadrupole case. The strengths of focusing elements in both (a) and (b) (top parts) are adjusted for a zero-current phase advance $\sigma_\circ = 85^\circ$ in the matched beams. In all cases, z=0 is the location of the aperture plane.

The electron gun, a Pierce-type source, produces 4 keV, 175 mA pulses (5 μs)at a rate of 60 Hz. An aperture, 6.4 mm in diameter, is placed 12.4 cm from the cathode; the aperture size is roughly 1/3 the full beam size at that plane and results in an almost uniform, 17 mA beam entering the transport pipe. The beam diagnostics is a 2.54 cm (diameter) phosphor screen that can be moved from the aperture out to a distance of nearly one meter. The beam pictures are captured with a charge-coupled device (CCD) camera and then digitized and displayed using associated hardware and software.

Figures 2(a)-(b), top parts, show the fluorescent screen pictures from typical experiments. The beam is fairly uniform over a distance of about 30 cm downstream from the aperture; the density perturbation is first seen in the form of a bright ring roughly 10 cm from the first beam waist in the three-solenoid case [Fig. 2(a)], and near the plane between quadrupoles 2 and 3 in the solenoid-quad lattice, also about 45 cm from the aperture [Fig. 2(b)]. Further downstream, the ring moves inwards relative to the beam's edge, and a second ring emerges around 85 cm from the aperture. To aid in understanding the experiment, we have conducted 2-D and 3-D PIC simulations using the code WARP [9]. Details of the numerics and modeling of focusing elements are described thoroughly elsewhere in connection with simulations of the Maryland Electron Ring [10] and prototype injector experiments [11]. As is evident from Figs. 2(a)-(b) (bottom), the rings are also observed in the simulations, and agreement between the simulation and the experiment is good, although a difference in the phase of the perturbation is seen.

The simulations especially address the role of initial conditions. The phase of the perturbation is sensitive to the temperature profile, so starting the simulations at the beam waist upstream from the aperture [Figure 2(d)], and fully modeling the latter, yields the best agreement with experiment. Alternatively, a semi-Gaussian distribution with a parabolic temperature profile right after the aperture produces similar results.

We gain additional insights for understanding the density perturbation when we replace the truncated distribution in the simulation with an rms equivalent equilibrium distribution, such as a K-V. In that case, no rings appear whatsoever, and the beam distribution remains K-V for the rest of the channel. This leads us to believe that the wave-like perturbation is the result of a large force imbalance or lack of equilibrium in a sheath at the beam edge, right after the aperture. As seen in Fig. 2(d), middle plot, the phase space is trapezoidal and tilted, with anomalous particle populations with relatively large velocities near the beam edge. In addition, the distribution lacks the spatial tails of an equilibrium thermal distribution (Maxwell-Boltzman), which are of the order of a Debye length [12]. In our case, the Debye length is 0.74 mm, which is non-negligible when compared to the beam radius near (and downstream of) the aperture, so the fraction of "missing" particles in a sheath one Debye length is significant. In summary, the truncated distribution is not only a non-equilibrium distribution, but also one where the departure from equilibrium is confined to the beam edge. As a consequence, the beam edge particles experience space-charge forces that are very different from those affecting the particles in the bulk of the beam. The resulting beam evolution in simulations of the solenoid-quadrupole case can be seen in the last two phase-space plots of Fig. 2(d).

Tracking of test particles moving near a model K-V beam (i.e. assuming the space charge forces arise from a uniform density beam with a sharp edge) reproduces correctly the onset of the perturbation in all experiments. In the model, test particles leave the beam near the edge of the aperture and are focused back into the beam. These results suggest that an electron flow component exists that explains the appearance of the first ring; the second ring, however, is most likely the result of a perturbation induced by the initial flow.

Finally, to examine the long term evolution of the beam, simulations were done in a uniform focusing channel over a distance of 20 m. The simulations are a "smooth approximation" version of the three-solenoid case, i.e. the beam has the same generalized perveance, and it's matched so its radius is constant, comparable to the average beam size in the experiments. As seen in Figure 2(c), the perturbation appears at a distance of about 70 cm from the aperture, and the oscillations persist for a few plasma periods ($\lambda_p \sim 1$ m in this case) and eventually diminish in amplitude as the beam evolves into equilibrium. Over the extent of the simulations, we observe no emittance growth associated with the perturbation, unlike other relaxation mechanisms [12]. Instead, the emittance oscillates slightly about its initial value, then levels off as the perturbation damps out.

Since collimation is used in many systems, the phenomenon described here may be fairly universal and worth of additional studies. First, a wider range of parameters and conditions (generalized perveance, emittance, aperture size and location, external focusing, etc.) in both experiment and simulations has to be explored to answer important questions about scaling, stability of the oscillations and emittance growth. Secondly, the suggestion that the collective phenomena involves two components must be further studied to understand the extent of the particle-flow component and how it gives rise to a transverse wave.

REFERENCES

1. M. Reiser et. al., these Proceedings.
2. T. P. Wangler et al., in IEEE Trans., NS-32, 2196 (1985).
3. I.M. Kapchinskij and V.V. Vladimirskij, in Proceedings of the international Conference on High Energy Accelerators, Geneva, 1959 (CERN, Geneva, 1959), p. 274.
4. R. L. Gluckstern, in Proceedings of the Linac Conference, Fermilab, 1970, p. 811.
5. R. C. Davidson, Physics of Nonneutral Plasmas, Addison-Wesley, Reading, MA, (1990).
6. Steven M. Lund and Ronald C. Davidson, Phys. Plasmas **5**, 3028 (1998).
7. S. M. Lund, J. J. Barnard, G. D. Craig, A. Friedman, D. P. Grote, H. S. Hopkins, T. C. Sangster, W. M. Sharp, S. Eylon and T. J. Fessenden, E. Henestroza, S. Yu, and I. Haber, Nucl. Instrum. Methods Phys. Res., A 345 (1998).
8. S. Bernal, R. A. Kishek, M. Reiser and I. Haber, "Observations and simulations of transverse density waves in a collimated space-charge dominated electron beam", to appear in Phys. Rev. Lett., Spring, 1999.
9. A. Friedman, D. P. Grote, and I. Haber, Phys. Fluids B **4,** 2203 (1992).
10. R. A. Kishek, S. Bernal, M. Venturini, M. Reiser, and I. Haber, to appear in Proc. ICAPS'98 (1999).
11. S. Bernal, P. Chin, R. A. Kishek, Y. Li, M. Reiser, J. G. Wang, T. Godlove, and I. Haber, Phys. Rev. ST Accel. Beams **4,** 044202 (1998).
12. M. Reiser, Theory and Design of Charged-Particle Beams, Wiley & Son, New York (1994).